

Measurement of the Muon-Spin Photon Angular Correlation in Radiative Muon Capture on ^{40}Ca

Inaugural Dissertation

zur Erlangung der philosophischen Doktorwürde
vorgelegt der
Philosophischen Fakultät II
der
Universität Zürich

von

Markus Walter Schaad
aus Zürich und Niederbipp

Begutachtet von Herrn Prof. Dr. Peter Truöl

Zürich 1987
Zentralstelle der Studentenschaft



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Abstract

For the radiative muon capture process on ^{40}Ca a measurement of muon-spin photon angular correlation has been performed at SIN. The arriving muons with an initial spin direction antiparallel to the beam were stopped in a ^{40}Ca target which was placed in a transverse magnetic field. For the precessing muons the angle between the muon-spin and the photon was measured using a stroboscopic method to make full use of the high muon flux available at SIN. To suppress neutrons the photons were converted to e^+e^- pairs in a lead converter and detected in a spectrometer consisting of 64 NaI modules. The exact number of neutrons not rejected by the neutron suppression mechanism was determined using the difference in topology for photon and neutron events in this modular detector. The photon spectrum in the energy range between 60 MeV and 90 MeV was further corrected for pion-induced and non-target associated background to obtain a clean radiative muon capture spectrum. The result for the energy-averaged asymmetry $\overline{\Gamma}_\gamma$ extracted from the time distribution of these photons is 0.94 ± 0.14 . From this we obtain for the induced pseudoscalar coupling constant a value of $g_P = (5.1^{+4.4}_{-7.0})g_A$ compared with the theoretical value in hydrogen of $g_P = 7g_A$.

Chapter 1

Introduction

1.1 Motivation for the Present Studies

A general answer to the motivation for radiative muon capture (*RMC*) experiments $\mu^- p \rightarrow n \nu_\mu \gamma$ is the additional information which can be deduced from the photon radiated by any of the charges or magnetic moments involved in the process. More specifically, the study of the structure dependent radiation reveals information on the interaction vertices and on the particles which is absent in the non-radiative process. Limited information can be deduced from ordinary muon capture (*OMC*) $\mu^- p \rightarrow n \nu_\mu$. In nuclei the basic process is influenced by the presence of nuclear matter and thus provides information on various effects which may lead to a modification of the coupling constants of the semileptonic weak interaction, in particular the induced pseudoscalar coupling constant g_P , by meson exchange currents or medium polarization. The importance of the muon-spin photon angular correlation has been recognized already in early papers, e.g. the one of Rood and Tolhoek [RT 65].

1.2 Previous Work

The history of radiative muon capture starts about 28 years ago with the first discussion of muon capture bremsstrahlung by Primakoff [Pri 59] and with the experiment of Conforto et al. [CCL 62], where the first $(\mu^-, \nu_\mu \gamma)$ events were actually seen. Most experimental attempts to investigate RMC were limited to the observation of

Table 1.1: Summary of experiments on muon-spin photon angular correlation.

$\bar{\Gamma}_\gamma$	Reference	
-0.32 ± 0.48	di Lella et al.	[DHR 71]
0.90 ± 0.50	Hart et al.	[Har+ 77]
0.82 ± 0.76	Frischknecht et al.	[Fri+ 80]
0.70 ± 0.20	Hasinoff et al.	[Has+ 84]
0.92 ± 0.26	Döbeli et al.	[Dob+ 86]

the integral ¹ and the differential rate. The experimental data on the muon-spin photon angular correlation are very scarce ² Table 1.1 gives a summary of these experiments. Insufficient discrimination against neutron background has troubled the first experiment [DHR 71] and led to a negative value for the photon asymmetry. The remaining four experiments claim a positive value for the photon asymmetry in agreement with theory but the second and the third report considerable errors. The experiment of Frischknecht et al. is a test experiment at SIN done by our group to demonstrate the feasibility of the stroboscopic method (Sec. 3.2). Hasinoff et al. is the preliminary analysis of an experiment at TRIUMF and was not published when we started the experiment. Döbeli et al. is also an experiment performed by our group with the same apparatus as the one used in this work. It reports on the analysis of a first set of data taken in April 1984, while the data on which we report here were taken in August 1984.

¹The analysis of an experiment of our group measuring the total RMC branching rate in a series of nuclei has only recently been terminated [Doe 87].

²For a review on RMC experiments see [GmT 86].

Chapter 2

Theory

In this work only those aspects of the theory needed to understand the experiment are given. For a more elaborate discussion the reader is referred to the specialized articles on this topic¹

2.1 Ordinary Muon Capture

Ordinary muon capture (OMC) is the reaction

$$\mu^- p \rightarrow n \nu_\mu \quad (2.1)$$

The ordinary muon capture amplitude can be written as

$$\mathcal{M}_{\mu c} = \frac{G_F}{\sqrt{2}} \bar{u}_n (V_\mu - A_\mu) u_p \bar{u}_\mu \gamma_\mu (1 - \gamma^5) u_\nu \quad (2.2)$$

The most general forms of V_μ and A_μ are

$$V_\mu = g_V(q^2) \gamma_\mu + i g_M(q^2) \sigma_{\mu\nu} \frac{q^\nu}{2m_n} + g_S^{(l)}(q^2) \frac{q_\mu}{m_l} \quad (2.3)$$

and

$$A_\mu = g_A(q^2) \gamma_\mu \gamma^5 + i g_P^{(l)}(q^2) \gamma^5 \frac{q_\mu}{m_l} + g_T(q^2) \sigma_{\mu\nu} \frac{q^\nu}{2m_n} \quad (2.4)$$

where

$$g_S = \frac{g_S^{(l)}}{m_l}, \quad g_P = \frac{g_P^{(l)}}{m_l}. \quad (2.5)$$

$G_F = 1.03 \times 10^{-5} m_p^2$ designates the Fermi coupling constant, the γ_μ the Dirac γ -matrices with $\gamma^5 = i\gamma_0\gamma_1\gamma_2\gamma_3$ and the other constants are defined as follows:

¹e.g. [GmT 86, CG 85, GO 81, CRS 80].

g_V : Vector coupling

g_A : Axialvector coupling

g_S : Scalar coupling

g_M : Weak magnetism

g_P : Pseudoscalar coupling

g_T : Tensor coupling

Since strong interaction is invariant under G-parity and if second-class currents are forbidden equations 2.3 and 2.4 are simplified since

$$g_S = g_T = 0 \quad (2.6)$$

If one starts to write down the matrix element as a sum of contributions from hadronically “naked” nucleons, strong vertex corrections and one-pion exchange (OPE) we see that only the one-pion exchange contributes to g_P . The OPE amplitude can be written as

$$\text{Vertex}(n \rightarrow p\pi) \times \text{Propagator}(\pi) \times \text{Vertex}(\pi \rightarrow e\nu)$$

Including vertex corrections one gets

$$\frac{g_P^{(l)}(q^2)}{m_l} = -\frac{f_\pi g_0 \sqrt{2}}{q^2 - m_\pi^2} F(q^2) \quad (2.7)$$

with the assumption that $F(q^2 = 0) \simeq F(q^2 = m_\pi^2) \simeq 1$ ($F(q^2)$ slowly varying).

To relate g_P and g_A one requires additionally partial conserved axialvector currents (PCAC)

$$\lim_{m_\pi \rightarrow 0} \frac{\partial A_\mu}{\partial x_\mu} = 0 \quad (2.8)$$

which leads then to the famous Goldberger-Treiman relation [GT 58]

$$g_A(q^2 = 0) \simeq f_\pi g_0 \frac{1}{\sqrt{2}m_p} \quad (2.9)$$

Comparing the Goldberger-Treiman relation with equation 2.7 we get the PCAC prediction for g_P

$$g_P^{(l)}(q^2) = g_A \frac{2m_p}{m_\pi^2 - q^2} m_l \quad (2.10)$$

The contribution of the pseudoscalar coupling to a certain reaction depends strongly on the momentum transfer in the reaction as can be seen from equation 2.10. Therefore the pseudoscalar coupling does not significantly contribute to β -decay where the momentum transfer is small. Ordinary muon capture is a much better candidate for the quantitative investigation of the pseudoscalar coupling. Here the momentum transfer is $q^2 \simeq -0.9m_\mu^2$ and we get from equation 2.10

$$g_P^\mu(q^2 = -0.9m_\mu^2) \simeq 7g_A \quad (2.11)$$

The observables in ordinary muon capture are

1. Capture rate
2. μ -spin neutron angular distribution for polarized muons
3. Neutron helicity

However for the experiment several problems arise:

1. Detection of the final state neutron
2. Imprecise knowledge of the initial quantum state (para/ortho $p\mu p$) for hydrogen.
3. Isolation of a specific nuclear transition for nuclear muon capture.

Despite these difficulties experiments in hydrogen, deuterium, in $A = 12$ and $A = 16$ systems have been done. Unfortunately they deduce values for g_P in a wide range and even the most precise among them report errors larger than 25%, as shown in Table 2.1 .

Table 2.1: Values of induced pseudoscalar coupling constant determined from ordinary muon capture rates in some light nuclei (Table from [GmT 86]).

Target	g_P/g_A	Reference	
^1H	7 ± 1.5	Bardin et al.	[Bar+ 81]
^{12}C	9 ± 1.7	Roesch et al.	[Roe+ 82]
	13.2 ± 2	Pathasaranthi, Sridhar	[PS 81]
	$10.1^{+2.4}_{-2.6}$	Kuno et al.	[Kun+ 84]
	~ 12.5	Heath, Garvey	[HG 85]
^{28}Si	13.3 ± 3	Pathasaranthi, Sridhar	[PS 81]

2.2 Radiative Muon Capture

Because of the above problems, one is led to the idea of using radiative muon capture (RMC) as a testing ground for the pseudoscalar coupling. RMC is the process where in the final state an additional high energy photon is produced

$$\mu^- p \rightarrow n \nu_\mu \gamma \quad (2.12)$$

There are essentially three types of models used for the calculation of the RMC amplitude for the free proton². One of them, the *diagram treatment*, uses the Feynman diagrams shown in Figure 2.1 (Method of [RT 65]). The amplitude is the sum of the contributions of all graphs. The results of the different models differ very little.

The advantages of RMC over OMC are

1. no neutron detection is necessary
2. At the high energy end of the photon spectrum the amplitude involving g_P is enhanced by a factor of $\simeq 3$ as compared to OMC.

The disadvantage is the very low branching ratio of $\Lambda_{RMC}/\Lambda_{OMC} \simeq 10^{-5}$ which prevented measurements of RMC in hydrogen, where even Λ_{OMC} is very small compared to the decay rate. A way out of this

²For a comparison of the models refer to [GmT 86].

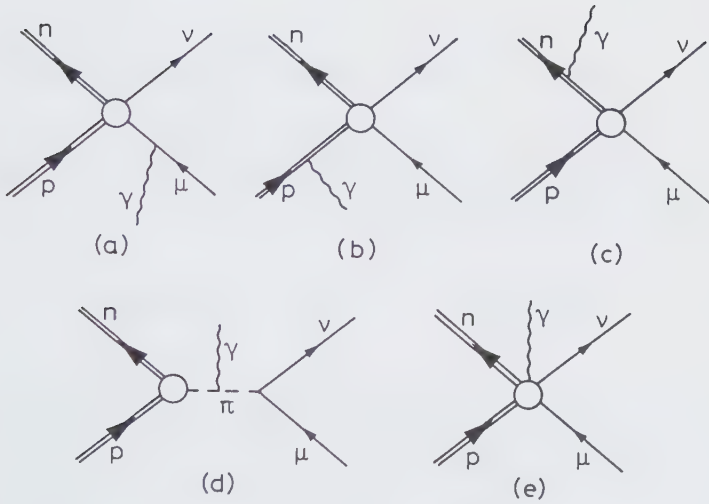


Figure 2.1: Feynman diagrams contributing to radiative muon capture. Photons are attached to all external or internal lines containing charges or magnetic moments (from [RT 65]).

problem is to study RMC in complex nuclei i.e.

$$\mu^-(A, Z) \rightarrow (A, Z-1)\nu_\mu\gamma \quad (2.13)$$

instead of the elementary process because $\Lambda_{\mu c} \propto Z_{eff}^4$, where $Z^3 < Z_{eff}^4 < Z^4$. However using high Z nuclei creates new problems, namely

1. recalculation of the elementary amplitude for the case of many particles
2. summation over the final states of the nucleus.

Various models have been discussed, which agree on two aspects

1. the photon asymmetry is only to a small extent model dependent
2. the shape of the energy spectrum depends not significantly on the model.

2.3 Observables in Radiative Muon Capture

Possible observables for a detected photon in RMC are differential and integral rate and the angular distribution of photons with respect to the direction of the muon spin³.

The differential rate can be written as

$$\frac{d\Lambda_\gamma(k, \theta_{\mu\gamma})}{dk \cdot d(\cos \theta_{\mu\gamma})} = \frac{d\Lambda(k)}{dk} (1 + \Gamma_\gamma(k) \cos \theta_{\mu\gamma}) \quad (2.14)$$

where k denotes the photon energy, $\theta_{\mu\gamma}$ the angle between muon spin and photon emission direction and $\Gamma_\gamma(k)$ the photon asymmetry in function of the photon energy. In this work we are interested in the latter quantity $\Gamma_\gamma(k)$, (which represents the muon-spin photon directional distribution) as an alternative approach to a determination of g_P instead of the usual rate measurements. The dependency of Γ_γ on g_P can be written as

$$\Gamma_\gamma(k) \simeq \frac{g_V^2 + 3g_A^2 + 2g_A g_P \eta}{g_V^2 + 3g_A^2 + 2g_A g_P \eta + 2g_P^2 \eta^2}, \quad \eta = \frac{m_\mu}{2m_p} \quad (2.15)$$

and calculations show that Γ_γ is only weakly energy dependent. Due to the very low rate of RMC we will measure only an energy averaged asymmetry $\overline{\Gamma_\gamma}$.

2.4 Choice of Target

The fundamental quantity of interest for an asymmetry measurement is the residual muon polarization P_μ at the instant of the muon capture. Among the effects which reduce the residual polarization, the

³Theoretically there are two additional observables: the photon circular polarization and the photon-neutrino directional distribution but at least as presently seen, they are hardly of any experimental interest.

most important individual effect comes from the muon depolarization in the target. After the muon has been stopped in the target it gets captured by the atom and cascades down to the $1S$ -level. During this cascade a depolarization of the muon occurs due to spin-spin and spin-orbit interaction. It is easier to accomplish an asymmetry measurement with a decent precision if the residual polarization is bigger. This leads immediately to spin-zero nuclei where the depolarization is less than in non-spin-zero nuclei due to the absence of spin-spin interaction. From theoretical calculations in agreement with experiments [Muk 77] the depolarization in spin-zero nuclei is known to be $1/6$. Among the spin-zero nuclei mainly those with doubly closed shells ($A = 4n$) are of interest because for them the ground state wave functions are comparatively simple and (therefore) reliable nuclear models exist.

These arguments lead to the choice of a ^{40}Ca target. Furthermore for ^{40}Ca calculations exist which predict the value of the asymmetry for certain values of the pseudoscalar coupling constant g_P . Moreover ^{40}Ca is a soft, but solid metal which can be handled fairly easily apart from the minor problem that it is hygroscopic. For ^{40}Ca the capture rate is $\Lambda_{OMC} = 31.8 \times 10^5$ and $\Lambda_{OMC} = (25.5 \pm 0.5) \times 10^5$ for theory and experiment respectively [Muk 77] and the branching ratio $\Lambda_{RMC}/\Lambda_{OMC}$ measured by two recent experiments is $(2.30 \pm 0.30)10^{-5}$ [Doe 87] and $(1.96 \pm 0.17)10^{-5}$ [Fri+ 85] respectively.

2.5 Experimental Aspects

The following problems arise with experimental work in radiative muon capture

Low intrinsic rate

Calculations give $\Lambda_{RMC} = 0.018s^{-1}$ for the elementary RMC reaction, which means that the number of photons per stopped muon is of the order of 10^{-8} . Therefore higher Z targets have to be used.

Bremsstrahlung

Photons from the radiative decay of the electron

$$\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e \gamma$$

(*internal bremsstrahlung*) and bremsstrahlung from muon-decay electrons in the target

$$\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e, e^- \rightarrow e^- \gamma$$

(*external bremsstrahlung*) produce a huge background to the photons from RMC extending up to energies of $E_\gamma \simeq m_\mu c^2/2 \simeq 53 \text{ MeV}$. Therefore only RMC photons with $E_\gamma > 53 \text{ MeV}$ are accessible to the experiments.

Neutron background

Depending on the energy transfer to the nucleus during the capture process the nucleus can be left in an unbound state which means that the muon capture process is most likely to be followed by neutron emission. For ^{40}Ca the neutron spectrum can be described as

$$N(E_n) = N_0 \exp(E_n/E_0, \text{ with } E_0 \simeq 9.5 \text{ MeV} \quad (2.16)$$

with a kinematical endpoint of 92 MeV [vdP+ 86, Koz+ 85]. The yield for this process is still about 100 times bigger than that of RMC and has troubled earlier RMC measurements [DHR 71].

Chapter 3

Experiment

3.1 $\mu E1$ Beam

At SIN the primary proton beam from the cyclotron has an energy of $E_p = 590$ MeV with a current of up to $150\mu A$ (1984). Due to its radiofrequency (RF) acceleration the beam has a definite time structure which is also reflected in the secondary beams and in the background: pions, muons and background electrons arrive in bunches of a certain length, at definite times with respect to RF and these bunch structures are repeated every period. The cyclotron RF is $\nu = 50.6328\text{MHz}$ which is equivalent to a period of $T_{RF} = 19.75004\text{ns}$ (time between two successive proton bursts).

3.1.1 The Muon Operation Mode

The $\mu E1$ area in which our experiment took place gets its muons from SIN's μ -channel I[SIN 81]. The muon collection from pion decay is performed by a superconducting solenoid of $8m$ length and has a maximum field strength of 50 Tesla. Table 3.1 gives a summary of the $\mu E1$ beam properties.

In normal operation mode the pion injection system was set to π^- with a momentum $p_{\pi^-} = 220$ MeV/c. The muon extraction system was set to select μ^- from backward decay with a momentum $p_{\mu^-} = 125$ MeV/c. Backward decay muons were selected to obtain a better π^- -suppression than is possible for forward decay muons.

A muon beam develops as the pions undergo weak decay during

Table 3.1: Summary $\mu E1$ beam properties.

Muon Operation Mode	
π^- -momentum	$p_{\pi^-} = 220 \text{ MeV}/c$
μ^- -momentum	$p_{\mu^-} = 125 \text{ MeV}/c$
μ^- -polarisation	$P_{\mu^-} \simeq 70\%$
π^- -contamination	$\pi^-/\mu^- \simeq 5 \times 10^{-4}$
e^- -contamination	$e^-/\mu^- \simeq 10^{-2}$
n -contamination	not quantitatively known
Spot size (measured)	$7 \times 10 \text{ cm}^2$
μ^- -spin orientation	antiparallel to beam axis
μ^- -flux	26MHz at $I_p = 150 \mu\text{A}$
Momentum bite	$\Delta p/p \simeq 13\%$ (FWHM)

their flight through the muon channel. In the pion rest frame the decay is isotropic. The right handed helicity of final state $\bar{\nu}_\mu$ and the angular momentum conservation give rise to a maximal parity violation. In the laboratory frame muons with the appropriate momentum (within a finite momentum band) are selected. All muons with momenta, which do not lie in axis of the pion momentum are depolarized (*kinematical depolarization*). The degree of depolarization depends on the acceptance of the muon extraction system and one has to make the optimal choice between beam polarization and beam rate. The magnitude of the kinematical depolarization can be calculated approximatively by [Wei 67, Muk 77]

$$P_\mu \simeq 1 - 2(\Delta E/m_\mu c^2) = 0.83, \quad \Delta E = 97 \text{ MeV} \quad (3.1)$$

whereas the quoted value is only ~ 0.70 [SIN 81].

For these settings a μ^- -flux of 30MHz with a proton beam current of $100 \mu\text{A}$ into an area of $10 \times 10 \text{ cm}^2$ is reported. The beam has a typical spotsize of $6 \times 4 \text{ cm}^2$ (FWHM) at 50 cm downstream from the last quadrupole and a momentum bite of $\Delta p/p \sim 13\%$ (FWHM). Since our apparatus did not allow to move closer than 1 m to the last quadrupole and the original beryllium pion production target had been replaced by a carbon target we received only about $2/3$ of the quoted μ^- -flux. This was partially compensated by a higher proton

beam current of $120 - 150\mu A$. We measured a beam spot of about $7 \times 10\text{cm}^2$ (FWHM) and a μ^- intensity of about 26MHz at $150\mu A$ through our $20 \times 20\text{cm}^2$ hodoscope counter.

The quoted π^- -contamination for this operation mode is 10^{-4} but previous measurements from our group indicated a π^- -contamination of the order of 10^{-3} . A large source for n and γ background is the muon beam itself (μ^- -capture and μ^- -decay). A strong source of n-background is also the proton beam dump which is close to $\mu E1$ although strongly shielded by concrete walls.

3.1.2 The Pion Operation Mode

Very useful for energy and time calibration of the detector system was the possibility to switch (or rather “to force”) the $\mu E1$ -beam into a pion extraction mode. By selecting the same momenta for the pion injection system and the muon extraction system a beam could be generated which contained about 60% e^- , 10% μ^- and 30% π^- . The pion injection system and the muon extraction system were both operated at $p_{\pi^-} = p_{\mu^-} = 146 \text{ MeV}/c$ which is the maximum momentum possible for the muon extraction system. Even with the intensity slits nearly closed we still measured an intensity of 30MHz particles through the hodoscope counter at a proton beam current of $150\mu A$. The π^- were singled out from the other particles by means of a time of flight (TOF) window with respect to the RF-burst.

3.2 Experimental Concept

To measure the asymmetry parameter Γ_γ of the μ -spin photon angular distribution we use in principle the same method as in μSR experiments, i.e. the measurement of the angle $\theta_{\mu\gamma}$ between the muon-spin photon emission direction is transformed to a time measurement.

The ^{40}Ca target is placed in a transverse magnetic field. The arriving polarized muons are slowed down in the degrader and subsequently stopped in the target. There they start to precess with the

Larmor frequency ω_L

$$\omega_L = g_\mu \cdot \frac{\mu_B}{\hbar} \cdot \frac{m_e}{m_\mu} \cdot B \quad (3.2)$$

The direction of precession is in the positive direction of a right handed reference system with respect to the magnetic field direction. By measuring the time between a μ^- stop in the target and the arrival of a γ (e^- , e^+) in the NaI-detector the angle $\theta_{\mu\gamma}$ and thereby the asymmetry (modulo 2π) can be determined.

3.3 The Stroboscopic Method

In order to retain a finite polarization of the muons in the target one has two options:

1. Keep the muon rate low enough in comparison with the inverse muon lifetime $(\tau_{\mu^-})^{-1}$. In this case many successive bunches will be empty and on average only one muon at a time will be in the target.
2. If the muon rate is high (i.e. $\sim 20\text{MHz } \mu^-$ as in our case) many new muons will arrive with successive bunches ($\sim 1\mu^-$ every 2.5 bunches). Therefore the Larmor frequency must match the beam burst repetition frequency (or one of its harmonics). This makes all the spins of the "old" muons, which are precessing in the target, pointing in the same direction as the spins of the arriving "new" muons. All muons in the target precess in phase. If this is not the case, no net polarization will build up in the target and therefore no asymmetry from a decay or capture process can be detected.

Because of the low intrinsic rate of the RMC process a high muon rate is essential for doing an RMC asymmetry measurement in a reasonable time and as explained in Section 3.1 the $\mu E1$ -beam at SIN is very well capable of delivering a high rate of μ^- . Therefore the stroboscopic method has to be used.

The value of the transverse magnetic field which makes the Larmor frequency ω_L equal to the beam RF frequency Ω_{RF} can be calculated from Equation 3.2 to $B_0 = 3736G$.

The stroboscopic method was pioneered by Klempt et al. [Kle+ 82]. The Larmor frequency and the beam burst repetition frequency must match within the uncertainty introduced by the muon lifetime

$$|\omega_L - m\Omega_{RF}| \leq 1/\tau_\mu, \text{ with } \Omega_{RF} = 2\pi\nu_{RF} \text{ and } m = 1, 2, \dots \quad (3.3)$$

With a $1/\tau_\mu$ of about 3MHz and 0.5MHz for μ^- and μ^+ respectively the equality must be fulfilled within $\sim 6\%$ and $\sim 0.9\%$ ($m = 1$).

3.3.1 Asymmetry Function for the Stroboscopic Method

Klempt et al. [Kle+ 82] show in detail the derivation of the resulting asymmetry function for the case of the stroboscopic method and only a short summary is given here.

The periodic time structure of the incoming muon beam results in a periodic muon stopping rate $B(t)$ with $B(t) = B(t + nT_{RF})$. The photons of the RMC process (or the electrons of the muon decay) are emitted in the direction of a detector with a finite solid angle and centered at angle ϕ in the plane of the precession. Electronically defined gate functions $G_j(t)$ (in our case: bin j of TDC), which are periodic in time and phase locked to the master oscillator of the radiofrequency are used and there are N consecutively, non-overlapping gates. Every detected particle therefore falls into exactly one of these gates $G_j(t)$, $j = 1, \dots, N$.

To determine the asymmetry function, we are interested in the total number of particles falling into gate $G_j(t)$ as a function of the Larmor precession frequency ω_L . The probability for a decay or capture of a μ^- (μ^+) stopped at time t_0 in the target and precessing there with Larmor frequency ω_L , with successive emission of a particle (γ, e^-, e^+) in the direction of a detector at angle ϕ is given by

$$\Lambda(t) = (1/\tau_\mu) \exp[-(t - t_0)/\tau_\mu] (1 + \Gamma \cos[\omega_L(t - t_0) - \phi]) , \text{ with } t \geq t_0 \quad (3.4)$$

This probability has to be integrated over the finite solid angle of

the detector, the gate-open time and over the number of all muons which have entered the target and did not yet decay.

It is assumed that the beam burst can individually be described by a Gaussian

$$b(t) = (\kappa T \sqrt{\pi})^{-1} \exp[-(t/\kappa T)^2] \quad (3.5)$$

and the muon beam is a superposition of beam bursts

$$B(t) = B \sum_{n=-\infty}^{\infty} b(t - nT) \quad (3.6)$$

where B is the average number of stopped muons per burst. Then for a constant fractional width λ of the TDC channels the stroboscopic line shape can be written as

$$N(t_j) = N_0 \lambda \left[1 + \sum_{n=-\infty}^{\infty} \Gamma e^{-(m\pi\kappa)^2} \frac{\sin(m\pi\lambda)}{m\pi\lambda} \frac{(\cos \psi_{m,j} - x \sin \psi_{m,j})}{1 + x_m^2} \right] \quad (3.7)$$

where $N(t_j)$ is the number of events falling into TDC channel j , N_0 is the total number of detected particles (γ , e^- , e^+), $x_m = (\omega_L - m\Omega)\tau_\mu$ and $\psi_{m,j} = m\Omega(t_j - t_0) - \phi$. Equation 3.7 shows a resonant behaviour (second and third factor in the summation) whenever the muon-spin precession frequency ω_L crosses one of the harmonics of the burst repetition frequency Ω .

In the proximity of a resonance i.e. for $x_m \ll 1 \ll \Omega\tau_\mu$, the summation over all m yields one dominant contribution. By choosing $m = 1$ and neglecting non-resonating poles the stroboscopic line simplifies to

$$N(t_j) = N_0 \lambda [1 + \Gamma_{eff} (\cos \psi_j - x \sin \psi_j)] \quad (3.8)$$

where Γ_{eff} is the called *effective asymmetry* defined as

$$\Gamma_{eff} = \Gamma e^{-(\pi\kappa)^2} \frac{\sin(\pi\lambda_j)}{\pi\lambda_j} \frac{1}{1 + x^2} \quad (3.9)$$

with $x = (\omega_L - \Omega)\tau_\mu$, where the dependence of Γ_{eff} on the muon precession frequency and implicitly on the magnetic field is hidden. At the exact resonance value $x = 0$ the asymmetry line shape is then

$$N(t_j) = N[1 + \Gamma_{eff}(\lambda) \cos(\Omega(t_j - t_0) - \phi)] \quad (3.10)$$

During the experiment the data sampling was done with a fractional gate width $\lambda = 0.005$ (0.1ns/bin) but was rebinned later for the fit to $\lambda = 0.05$ (1.0ns/bin). The quotient Γ_{eff}/Γ which is the asymmetry reduction due to the use of the stroboscopic method can be calculated for Equation 3.9. For a measured beam burst width of 5.5ns we get $\kappa = 0.17$, $e^{-(\pi\kappa)^2} = 0.76$ and $\frac{\sin(\pi\lambda)}{\pi\lambda} = 0.996$. As the latter term is ~ 1 we conclude that our fractional gate width is small enough. The width of the resonance can be calculated from Equations 3.2 and 3.9

$$\Delta\omega(\text{FWHM}) = \frac{2}{\tau_\mu} \quad (3.11)$$

and

$$\frac{\Delta\omega}{\omega} = \frac{\Delta B}{B_0} \quad (3.12)$$

With the lifetimes of $\tau_{\mu^+} = 2.2\mu\text{s}$ for positrons and $\tau_{\mu^-} = 343\text{ns}$ for electrons in ^{40}Ca results in $\Delta B_{\mu^+} = 11\text{G}$ and $\Delta B_{\mu^-} = 69\text{G}$.

3.4 Apparatus

3.4.1 Introduction

This Section describes the general setup of our detection system in area μE1 and gives a more detailed description of the principal components of the detection system: the two γ/e^- detectors.

3.4.2 The Beam Telescope

The experimental arrangement at the SIN superconducting muon channel I in experimental area μE1 is shown in Figure 3.1

The number of incoming particles was determined by means of a beam-defining telescope in the beam axis consisting of four plastic scintillator counters. These counters are called $\mu 1 \cdots \mu 4$ in downstream order. Table 3.2 gives the dimensions of the scintillators used in this experiment. The scintillator $\mu 1$ was actually a hodoscope made up of 6 individual plastic scintillator strips. Each of them was equipped with a photomultiplier. This subdivision was necessary to

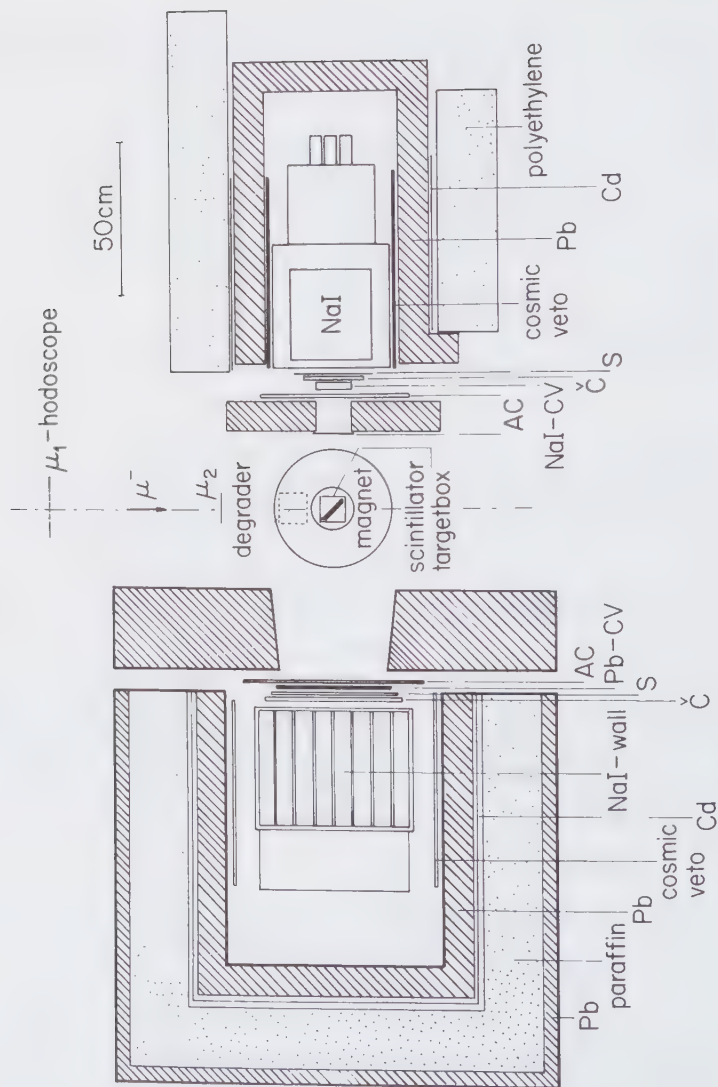


Figure 3.1: The experimental arrangement

Table 3.2: Summary of beam telescope scintillator properties.

Name	Dimensions	Remarks
$\mu 1$	$20 \times 25 \times 0.5 \text{cm}^3$	6-fold hodoscope Front side of target box Rest of target box
$\mu 2$	$10 \times 10 \times 0.5 \text{cm}^3$	
$\mu 3$	$8 \times 8 \times 0.1 \text{cm}^3$	
$\mu 4$	$8 \times 8 \times 0.2 \text{cm}^3$	

handle the high rates mentioned in Section 3.1. Counter $\mu 2$ was simply used as to define the beam in front of the degrader and counter $\mu 3$ between degrader target defined the number of particles entering the target. It was chosen to be very thin (1mm) to avoid as much as possible stopping particles in the counter itself. Counter $\mu 4$ was used as an anti-counter to mark primary particles which were not stopped in the target. The μ^- were slowed down in a degrader and brought to rest in a ^{40}Ca target. Table 3.3 gives an overview of the target properties. The target was located inside a pair of ‘‘Helmholtz’’-like coils producing a transverse magnetic field B_0 of 3736G . To be able to produce a field of this strength with enough homogeneity the coils had to be encased by a cylindrical iron yoke for flux return. The magnet had its axis in vertical direction and holes were provided in the horizontal plane of the iron yoke for the incoming (and outgoing)

Table 3.3: Summary of ^{40}Ca target properties.

^{40}Ca Target	
Dimensions	$8.5 \times 7.0 \times 2.3 \text{cm}^2$
Chemistry	soft, solid, hygroscopic metal
Shape	polyepipedal
Orientation	45 degree to beam axis
Density	$\rho = 1.540 \text{g/cm}^3$
Stopping power	5.00g/cm^2
Purity	97%
μ^- -Lifetime	$(343 \pm 3) \text{ns}$ [ESW 66]
Degrader	CH_2 , 10cm length

beam in 0/180 degree directions as well as for the outgoing secondary particles in 90/270 degree directions.

Additional holes on top and bottom allowed the insertion of a scintillator box (*target box*) containing the target. This target box was used to determine the fraction of particles stopped in the target during low rate calibration runs. During the actual data taking the target box was removed.

Perpendicular to the beam two γ/e^- detecting systems were arranged with NaI crystals as their main components. In early test experiments both sides were equipped with almost identical cylindrical NaI one-crystals of 22.7cm diameter and 33cm length (12.7 radiation lengths). Later one of the two cylindrical detectors was replaced by a larger 64 crystal NaI detector (hence forth: *NaI-wall*). All the data analysed in this work were taken with this bigger detector (left side of Figure 3.1).

3.4.3 The NaI-Wall Detector

The NaI-wall detector had been built as a γ -detector for a $\pi^+ \rightarrow e^+ \nu_e \gamma$ experiment by the University of Lausanne. Many of its basic properties have been studied in detail in the thesis of A. Bay [Bay 86]. It was modified by us to give a better neutron suppression.

This NaI-wall is composed of a matrix of 64 individual NaI(Tl) crystals each viewed by a photomultiplier. To protect the NaI against humidity and to limit thermal drifts somewhat the whole matrix is encased in a box of 2cm *Al* except on the front side where the *Al* is only 0.3cm thick. This box is housed in a second box: a multi-layer shielding against background radiation and cosmic muons. It is made up of a layer of 5cm *Pb*, a 20cm layer of borated polyethylene to thermalize neutrons, a thin foil of *Cd* (0.15cm) to capture thermalized neutrons, followed again by a layer of 10cm *Pb*. On the front side the polyethylene shielding is only 10cm thick and a rectangular window of $40 \times 40 \text{ cm}^2$ is without shielding to allow the particles from the target to enter the detector.

Inside this shielding box is a box of four plastic szintillators (TOP, BOTTOM, LEFT, RIGHT). Together with the front anticounter AC they

Table 3.4: Summary of NaI wall properties.

NaI-wall Properties	
Number of modules	64 (8×8)
Total active crystals size	$50.8 \times 50.8 \times 40.6 \text{cm}^3$
Single crystal size	$6.35 \times 6.35 \times 40.6 \text{cm}^3$
Distance from target center	67cm
Solid angle	$\Delta\Omega/4\pi = 0.0263$
Density	3.67g/cm^3
Energy resolution for γ of 129.4 MeV	
without converter	6% (FWHM)
with 4mmPb converter	14% (FWHM)

have a threefold function. Since they are efficient for charged particles they allow a) to veto charged particles which penetrate the shielding i.e. cosmics, b) to veto charged particles created in the capture process of the neutrons in the *Cd* foil and c) to eliminate photons or electrons which enter the detector correctly by the front hole in the shielding but lose a significant amount of their electromagnetic shower outside of the crystal array. Function c) allows to improve slightly the energy resolution at the price of a minimally reduced efficiency.

The modifications made by us were the following: we moved the front shielding block forward by about 10cm to allow the insertion of an *Pb* converter of $40 \times 40 \times 0.4 \text{cm}^3$ (≈ 0.7 radiation length), a lucite Čerenkov Č of 1cm thickness and a trigger counter system consisting of three parallel 0.5cm thick plastic scintillator strips (T1, T2, T3) to cover the entire $40 \times 40 \text{cm}^2$ of the converter. With the help of the plastic Čerenkov Č the photons converted into a e^+e^- -pair in the lead could be tagged.

3.5 Electronics

3.5.1 Beam Telescope Electronics

The beam telescope electronics allowed to monitor beam intensity, to measure the exact number of muons stopped in the target, to tag π^- in the beam with time of flight (*TOF*) versus the radiofrequency *RF* of the accelerator and to discriminate against e^- in the beam with pulseheight selection.

Also each of the individual plastic scintillator strips of the hodoscope and $\mu 1$ (the logical OR of all of them) gave a stop signal for a time measurement. The common start signal for all of these time measurements was given by *EVENT*. The seven TDC's are called *EVH1*, ..., *EVH6*, *EVM1* and the corresponding times are called Δt_{NaI-H1} , ..., Δt_{NaI-H6} and $\Delta t_{NaI-\mu 1}$. These time measurements are very important in the offline analysis to account for the π^- -induced background (Sec. 4.3.3).

3.5.2 NaI-Wall Electronics

This paragraph describes in detail the electronics of the NaI-wall which is shown in Figure 3.2

The analog signals from each of the 64 photomultipliers were sent through triaxial cables from the experimental area to the signal processors (*SP*) arranged in the distantly located electronics area. These analog signals were differential signals and there was no common ground between experimental area and electronics barrack. The signal processors produced for each channel three signals: a) a fast signal going into a constant fraction discriminator (*CFD*), which produced in turn a logical signal for event time determination and stop of a TDC, b) a first analog signal for energy measurement by an ADC and c) a second analog signal which was sent via an internal bus to a *trigger box (TB)*. The trigger box determined if the deposited energy in the entire NaI-wall exceeded a certain adjustable threshold. If this was the case the trigger box created a signal called **NaI_{HIGH}**.

In order to reduce as much as possible pile-up effects at higher rates the trigger box did not simply add all of the 64 energy signals

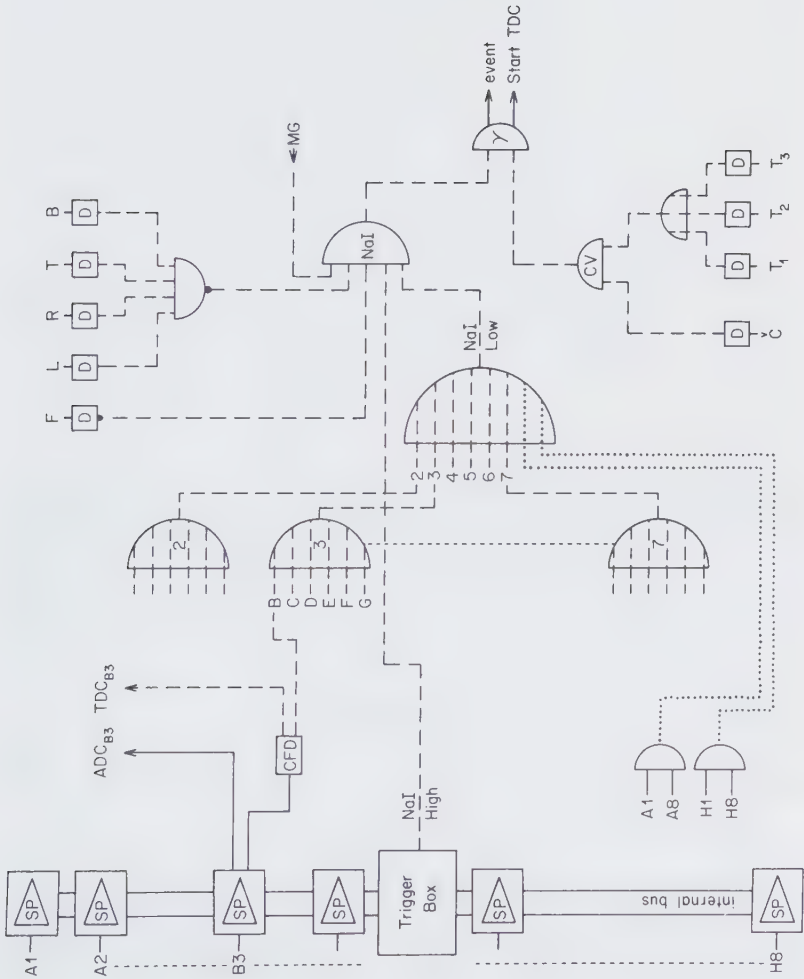


Figure 3.2: NaI-wall electronics. Solid lines indicate analog signals and long dashed lines logical signals. The dotted lines show logical signals which are only used for measurements of cosmic rays.

but instead determined the energy sum in each of the 49 groups of 4 adjacent bars (*quad*) and compared this energy with the selected threshold. Monte Carlo simulations of A. Bay [Bay 86] have shown that on an average 94% of the energy can be found in the quad with the maximum energy. Also the trigger box allowed to set the attenuation factor in the individual signal processors to be either 10 or 100. Thereby it was possible to measure either normal events with an energy of a few tens of MeV deposited per module or to do source calibrations with typical energies of ~ 1 MeV per module.

The 64 individual time signals were adjusted to be coincident within $\sim 0.5ns$ of each other by selecting the appropriate cable lengths. For each of the constant fraction discriminators one of the two outputs was fed into a corresponding TDC stop input. The start for all of these TDC's was given by the accelerator RF signal divided by 3 ($RF/3$) gated by *EVENT*.

An NaI_{LOW} signal was generated by a logical OR of any of the central 36 NaI modules. In order to avoid the center of an event shower being in any of the 28 boundary modules these modules were not included in the OR and could thus not trigger an event. Otherwise this would mean that a significant amount of the electromagnetic shower energy would be lost outside of the NaI array. The "Event-seen-in-NaI" condition NaI was given by a coincidence of

$$NaI = NaI_{LOW} \wedge NaI_{HIGH} \wedge \overline{COSMIC}$$

where

$$COSMIC = TOP \vee BOTTOM \vee LEFT \vee RIGHT$$

The NaI_{LOW} signal came directly from the logical OR of the 36 constant fraction discriminators and had a length of only $\sim 5ns$. It was therefore well defined in time and determined the time of NaI coincidence (NaI).

The NaI_{HIGH} signal was $\sim 20ns$ wide and determined the energy threshold without modifying the timing. We used constant fraction discriminators with low thresholds to get energy independent timing signals. However this did not suffice, as will be explained in Section

	1	2	3	4	5	6	7	8
A	1	2	3	4	5	6	7	8
B	9	10	11	12	13	14	15	16
C	17	18	19	20	21	22	23	24
D	25	26	27	28	29	30	31	32
E	33	34	35	36	37	38	39	40
F	41	42	43	44	45	46	47	48
G	49	50	51	52	53	54	55	56
H	57	58	59	60	61	62	63	64

Figure 3.3: Array of 64 NaI crystals in 8 rows and 8 columns. The dashed lines mark the central 6×6 modules; only one of these was able to trigger the event ($\text{NaI} = \text{NaI}_{\text{LOW}}$). The hatched area shows a typical quad.

4.2.7. With $\mathbf{e}' = \check{\mathbf{C}} \wedge (\mathbf{T}_1 \vee \mathbf{T}_2 \vee \mathbf{T}_3)$ an event on the side of the NaI-wall is given by

$$\mathbf{e}^- = \mathbf{AC} \wedge \mathbf{e}' \wedge \mathbf{NAI} \text{ (electron)} \quad (3.13)$$

or by

$$\gamma_{\text{conv}} = \overline{\mathbf{AC}} \wedge \mathbf{e}' \wedge \mathbf{NAI} \text{ (converted photon)} \quad (3.14)$$

or by

$$\gamma_{\text{non-conv}} = \overline{\mathbf{AC}} \wedge \overline{\mathbf{e}'} \wedge \mathbf{NAI} \text{ (unconverted photon)} \quad (3.15)$$

Runs taken with trigger condition 3.13 are called *Electron* runs and runs taken with trigger condition 3.14 are called *Gamma* runs. Trigger condition 3.15 was only used for time and energy calibration runs with beam in pion operation mode.

Two remotely controllable 32-channel power supplies were used for the NaI photomultipliers. With these power supplies the task of adjusting the output signals of all 64 channels to the same level (Sec.

3.6) was very much facilitated. To avoid too much heat dissipation near the NaI crystals the voltage division for the last four dynodes (where most of the current is drawn) was done outside of the NaI shielding.

3.6 Measurement

The actual measurements contained several steps:

Pedestal measurement

Determination of the stroboscopic field

Initial energy calibration of the NaI-wall

Energy calibration with sources

Energy calibration with cosmic muons

Energy calibration with pion reactions

Asymmetry measurements

3.6.1 Pedestal Measurement and Software Threshold

Any noise or DC-level present on the analog signal lines between the 64 photomultipliers in the experimental area and the signal processors in the electronics barrack was measured automatically at the start of every run. The ADC-gates were opened artificially (i.e. without an event being present) 100 times by the computer and the ADC values were read out, written to tape as *pedestals* and stored in the data acquisition program. During normal acquisition these pedestals were subtracted from the measured ADC values before writing them to tape. Only those ADC values which were surpassing an adjustable software threshold were recorded. This procedure helped to cut down noise in the detectors from spurious background and economized magnetic tape at a negligible loss of energy resolution.

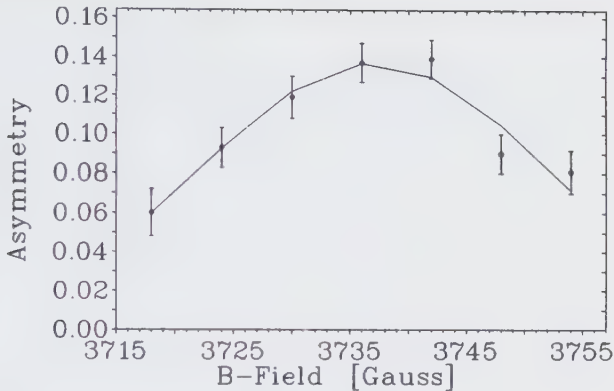


Figure 3.4: μ^+ -resonance curve with a width of 35G(FWHM).

3.6.2 Determination of the Stroboscopic Field

The magnetic field was initially set to about the calculated value (Sec. 3.2). Then the signs of the beam magnets were reversed to select μ^+ , the trigger was set to e^- (Sec. 3.5) and the ^{40}Ca target was used. Since a μ^+ is not captured and ^{40}Ca is a metal the initial spin orientation is retained. This leads to a larger experimentally measurable asymmetry of $\alpha_{e^+} \simeq 24\%$ instead of $\alpha_{e^-} \simeq 4\%$. This is essentially the averaged decay asymmetry diminished only by the finite time resolution of our detection system, the beam polarization, the field inhomogeneity and the deviation from the desired field. Due to the use of the stroboscopic method the calculated effective asymmetry (Eq. 3.9) is only about 3/4 of the above value. As already discovered by Klempt et al. [Kle+ 82] the measured effective asymmetry is even somewhat smaller ($\sim 2/3$) than the calculated.

The larger asymmetry for μ^+ makes it much easier to find the optimum field value. The μ^+ -resonance curve is shown in Figure 3.4. The field setting for μ^- -runs is less sensitive since the width of the resonance curve is inversely proportional to the muon lifetime (Eq. 3.11). As is shown in Section 3.3 the μ^- -resonance curve is about six

times wider than the μ^+ -resonance curve.

3.6.3 Initial Energy Calibration of NaI-Wall

The 64 photomultipliers (*PM*) were adjusted to give equal signal heights for the same amount of deposited energy in the respective module. All *PM*'s were operated at a high voltage of ~ 1200 – 1300 V, which allowed a dynamic range of 20–200 MeV for the total energy. This initial energy calibration was made with cosmic muons and the detailed procedure is explained in Section 4.2.1.

3.6.4 Energy Calibration with Sources

For the measurements with sources we used two iron plates, one with 64 ^{137}Cs sources and the other with 64 ^{88}Yt sources. These sources were positioned on the iron plates such that each NaI module faced one source. For these source calibrations the attenuation in the signal processors was set to factor 10 instead of factor 100. Hence the signal output of the signal processors corresponds to ~ 10 MeV. The threshold in the trigger box was set to very low values to allow triggering on these low signal values.

3.6.5 Energy Calibration with Cosmics

To be able to calculate the energy loss of cosmic muons through any of the individual crystals this passage had to happen in a predictable way. Therefore only those cosmic muons were selected which traversed the top and bottom cosmic anticounters and one entire column. Thus the trigger for this mode of data-taking was

$$\text{NAI} = \text{NAI}_{\text{LOW}} \wedge \text{NAI}_{\text{HIGH}} \wedge \text{COSMIC}$$

where NAI_{LOW} is a logical OR of any of the eight columns and any column is the logical AND of all the modules in this column. The attenuation was set as in normal data-taking to factor 100. From the extensive energy calibration measurements and the Monte Carlo simulations of A. Bay [Bay 86] the energy loss for cosmics traversing the NaI-wall in such a way is well established.

3.6.6 Energy Calibration with Pion Reactions

With the beam switched to pion operation mode (Sec. 3.1) the photons from radiative pion capture (*RPC*) and charge exchange (*CEX*) were recorded to do time and energy calibrations. Runs were made with trigger set for γ_{conv} as well as $\gamma_{non-conv}$ (Sec. 3.5) and with the targets CH_2 and ^{12}C .

3.6.7 Asymmetry Measurements

Selection of Target Events

Due to the high abundance of other material in the close vicinity of the target our signal to background ratio with the e^- - or γ -trigger was rather poor.

For the initial studies of detector acceptance and for rate calibrations we inserted additionally a μ_{stop} condition in the event trigger and turned the beam intensity down to $\sim 500\text{kHz}$ (μl). During normal runs this method did not significantly improve the signal to noise ratio, because with the high μ^- -flux ($\simeq 20\text{MHz}$) and the μ^- lifetime in ^{40}Ca (343ns) this condition would nearly always be fulfilled. We therefore decided to remove the target box to avoid additional background from its scintillators. The high background encountered made it necessary to devote a large fraction of the beam time to the measurement without target (*target OUT*).

Measurement of electron asymmetry

To be able to derive the theoretical asymmetry Γ_γ from the experimental photon asymmetry α_γ all depolarization factors should be known with sufficient precision. To determine these factors, we measured under the same experimental conditions for about one eighth of the beam time the asymmetry α_{e^-} of decay electrons for which the theoretical asymmetry is known. To do this we simply switched the trigger condition γ to the trigger condition e^- .

The event rate with this trigger condition was rather high (46Hz) and it took only about 22 minutes for one run (fill one tape). Table 3.5 gives a summary of the electron runs.

Table 3.5: Summary of e^- -runs.

	Target-IN	Target-OUT
Total Time	7.3 Hours	3.2 Hours
Number of Runs	20	8
Number of μ_1	29.82×10^9	26.13×10^9
Number of Events	1127×10^3	388×10^3

Measurement of gamma asymmetry

With a μ_1 rate of 20MHz the event rate was about 11Hz and one run took about 1.8 hours. Table 3.6 gives a summary over the photon runs. All the γ -asymmetry data were taken with the γ_{conv} trigger (Sec. 3.5).

Table 3.6: Summary of γ -runs.

	Target-IN	Target-OUT
Total Time	47.1 Hours	32.5 Hours
Number of Runs	32	14
Number of μ_1	3665.46×10^9	2460.00×10^9
Number of Events	1640×10^3	657×10^3

Chapter 4

Data Analysis

4.1 Summary

The data analysis contained several steps:

Individual Energy/Time Calibration Determination of time and energy calibration factors for all of the 64 NaI-wall modules.

Global Energy/Time Calibration Determination of global energy and time calibrations factors and offsets for all of the recorded registers¹.

Raw Data Analysis The raw data tapes (RDT) contain for each event all scalers and registers. The structure of each event was thoroughly tested and the registered data converted with the predetermined calibrations. The register RFEV was corrected for the energy-time dependence of the CFD's. Each of the NaI modules was subjected to the isochronous test. The EVH1 ... EVH6 were corrected for their offsets with respect to the individual NaI modules. New registers were calculated (e.g. NBBARS and ENERGY) and the following 10 registers (newly calculated ones and original ones with calibrations) were written to a dense data summary tape (DST): NBBARS, ENERGY (with 1 MeV resolution), RFEV, EVM1, EVH1 ... EVH6 (all with 0.5 ns resolution). For monitoring purposes all of the recorded and the calculated calibrated registers were histogrammed. The raw

¹A register is any of the recorded ADC's or TDC's.

data analysis was done in our institute on a LSI 11/73 running RSX11M.

Dense Data Analysis All recorded registers were histogrammed for various interesting energy regions. Each of the time histograms was corrected by the determined time-energy dependence as introduced by the CFD's. All runs with the same experimental conditions were added after long-term variations of time calibrations (shift) had been corrected. In these sets of sum histograms the backgrounds arising from neutrons and pions were determined and subtracted by a procedure which will be explained in Section 4.3. Then the *target-OUT* runs were subtracted from *target-IN* runs normalized to the number of incident muons to produce the proper signal from the target. The dense data analysis has been done on the SIN VAX Cluster.

Asymmetry Fit To determine the asymmetry, the function which will be explained in Section 4.6, was fitted to the experimental data in the RMC energy region and to the bremsstrahlung energy region for *gamma* runs and for *electron* runs. From the resulting two asymmetries α_e and α_γ the theoretical asymmetry Γ_γ was determined.

Comparison with Theory To determine the value of the induced pseudoscalar coupling g_P the theoretical asymmetry Γ was compared to the expected values from theoretical calculations for specific values of g_P .

4.2 Calibrations

4.2.1 Energy Calibration

As already briefly explained in Section 3.6 the energy calibration relies on the following reference points: calibration of the individual modules with sources (^{88}Yt and ^{137}Cs), energy loss of cosmic muons traversing entire columns and high energy photons from the RPC

Table 4.1: Summary of the energy calibration reference points.

		Energy	Reference Point
64 Sources	^{137}Cs	0.662 MeV	Peak mean
64 Sources	^{88}Y	0.898 MeV, 1.836 MeV	Peak mean
Cosmic muons		(28.7 ± 0.3) MeV	Half-height of raising slope
$\pi^- p \rightarrow \gamma n$	RPC	129.4 MeV	Peak mean

process (Sec. 4.2.4) for the calibration of the total energy. Table 4.1 gives a summary of the reference points.

4.2.2 Total Energy

With the trigger conditions explained in Section 3.5 electromagnetic showers starting too close to the boundary (outside of the inner square of 6×6 modules) or showers going out of the crystal array (detected by the cosmic anticounters) were discarded. The particle energy is in principle equal to the total energy deposited by an electromagnetic shower in the NaI-wall:

$$E = \sum_{i=1}^{64} E_i$$

with E_i being the energy in an individual crystal. However at high rates or with a high background this estimate of the true shower energy needs to be modified because of pileup effects. To avoid this the energy E_i of a module i was added to the sum only if the time difference of module i to the module with the maximum energy was smaller than a certain time which is called *isochronous time* T_{iso} . This time has been chosen to be $5ns$ which is long enough not to deteriorate the energy resolution by cutting away truly event related modules and short enough to get rid of a lot of accidental background.

4.2.3 Check of Total Energy and Energy Resolution

The photon energy is obtained in the following way. To account for the energy loss of the e^+e^- -pair in the converter, in the follow-

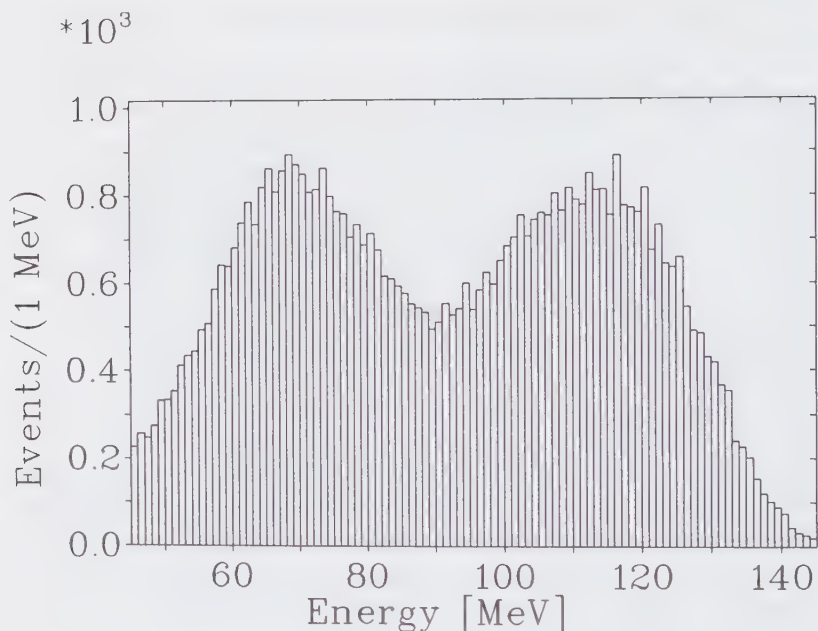


Figure 4.1: Energy spectrum of γ from π^- on CH_2 .

ing counters and in the aluminum entrance window, a constant energy offset was added to the energy sum of all bars fulfilling the isochronous time condition. The same was also done for electrons which lost already some of their initial energy in the target. These offsets were calculated from the energy loss of minimum ionizing particles and cross-checked with EGS Monte-Carlo calculations performed by Döbeli [Doe 87].

This procedure was checked with the energy spectrum of photons of π^- capture in hydrogen [BC'T 77]. This spectrum can be produced with sufficient accuracy by an appropriate subtraction of the energy spectra of converted photons from π^- on CH_2 and on ^{12}C targets (Sec. 3.6). figures 4.1 and 4.2 show these energy spectra. To this end the experimental data of the CH_2 and ^{12}C energy spectra were

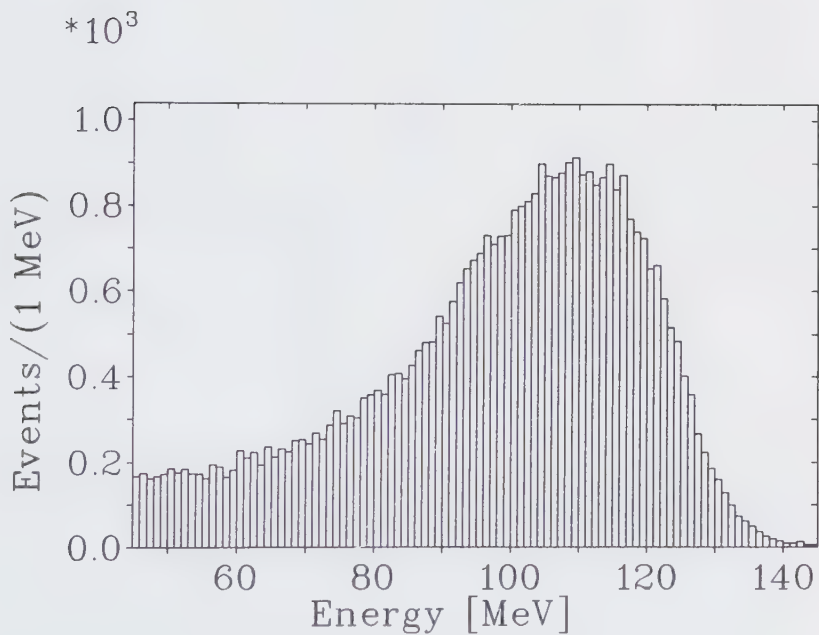


Figure 4.2: Energy spectrum of γ from π^- on ^{12}C .

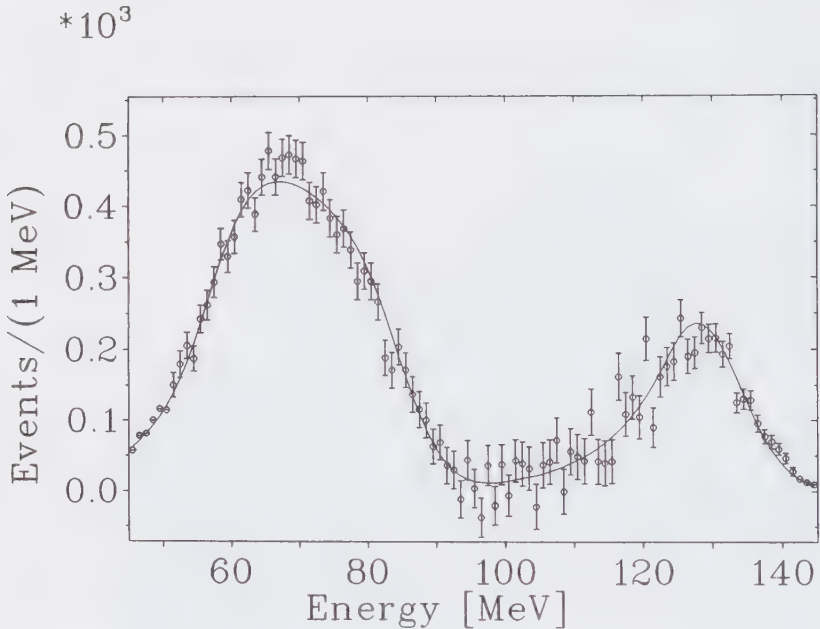


Figure 4.3: Energy spectrum from $CH_2 - {}^{12}C$ with fit of the expected hydrogen spectrum superimposed.

compared to a hydrogen spectrum folded with the resolution function and corrected for the variation of the acceptance as a function of energy. The resulting energy spectrum of the subtraction $CH_2 - {}^{12}C$ with the fit superimposed is shown in Figure 4.3. The fit yields a resolution for converted photons at 130 MeV of 14%. Table 4.2 shows the energy calibration. It exhibits a small, but negligible non-linearity in the energy region important for our experiment.

4.2.4 Time Calibration

For time and energy calibration measurements the $\mu E1$ channel was switched to π^- extraction mode as explained in Section 3.1. To

Channel	Energy [MeV]	Channel	Energy [MeV]
50	49.3	71	71.4
51	50.3	72	72.5
52	51.4	73	73.5
53	52.4	74	74.6
54	53.5	75	75.6
55	54.6	76	76.7
56	55.6	77	77.7
57	56.7	78	78.8
58	57.7	79	79.8
59	58.8	80	80.9
60	59.8	81	81.9
61	60.9	82	83.0
62	61.9	83	84.1
63	63.0	84	85.1
64	64.0	85	86.2
65	65.1	86	87.2
66	66.1	87	88.3
67	67.2	88	89.3
68	68.3	89	90.4
69	69.3	90	91.4
70	70.4	91	92.5

Table 4.2: Comparison of histogram channel with true initial γ energy.

obtain the time calibration photons from the radiative pion capture process (RPC) $\pi p \rightarrow \gamma n$ and the pion charge exchange (CEX) $\pi p \rightarrow \pi^0 n$, $\pi^0 \rightarrow \gamma\gamma$ were used. Since RPC and CEX processes occur instantaneously ($\tau \approx 10^{-12} ns$) these photons arrive with a very strict relation with respect to the RF frequency of the cyclotron and thus they provide ideal means for time calibration of the entire detection system.

A time calibration and offset correction was needed for the 64 individual time measurements $\Delta t_{RF-NaI(i)}$, ($i = 1, \dots, 64$) used for the asymmetry time spectrum. On the other hand the hodoscope time measurements Δt_{NaI-M1} , Δt_{NaI-H1} , $\dots$, Δt_{NaI-H6} did not require an absolute time calibration but an offset correction was indispensable. In addition all time measurements were corrected for energy dependence of the time measurements (*walk*) and for the long-term variations of time signals (*shift*).

4.2.5 Calibration of the Asymmetry Time Signals

The 64 individual time measurements $\Delta t_{RF-NaI(i)}$ ($i = 1, \dots, 64$), used for the asymmetry time spectrum, had to be calibrated as well as corrected for offsets against each other. As explained in Section 3.5 the $\Delta t_{RF-NaI(i)}$ values were sampled over three RF-periods ($\approx 60 ns$) and therefore three peaks of “prompt” photons are visible. These three peaks allow a calibration and the determination of the offsets. Figure 4.4 shows the $\Delta t_{RF-NaI(i)}$ time spectra for a typical column. The calibration of the 64 time signals was calculated to obtain a mean distance between two adjacent peaks equal to the RF period (19.75 ns). The offsets were calculated to bring all 64 first peaks to the arbitrary chosen channel 200. These calibration factors and offsets were introduced in the raw data analysis.

4.2.6 Offset Correction for Hodoscope Time Spectra

No absolute calibrations were needed for the hodoscope time spectra Δt_{NaI-H1} , $\dots$, Δt_{NaI-H6} but correction was necessary for the offsets of the individual NaI_{LOW} into the EVENT coincidence (Sec. 3.5 and

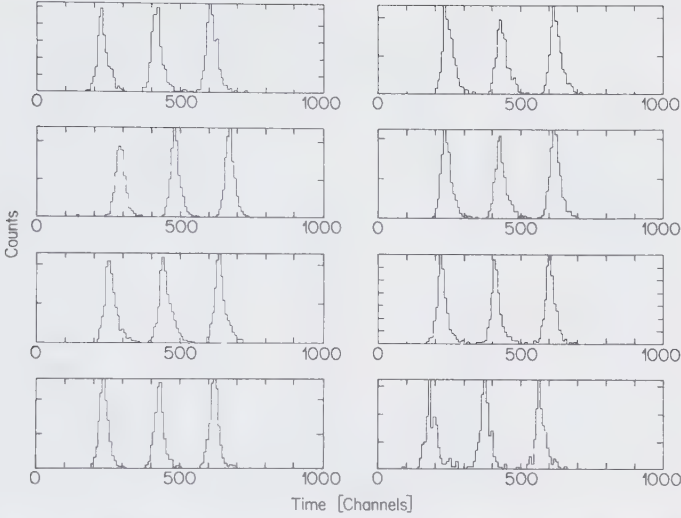


Figure 4.4: $\Delta t_{RF-NaI(i)}$ time spectra for a typical column. The detected particles are “converted photons” from RPC (beam: π^- , target: CH_2).

Fig. 3.2). The determination of these offsets was done in the same way as for the $\Delta t_{RF-NaI(i)}$ time spectra. The resulting offsets were introduced in the raw data analysis.

4.2.7 Energy Dependence of the Time Signals

For the procedure of the prompt subtraction, as explained in Section 4.5, it is crucial to assure that there is no energy dependence of the time measurement (*walk*). Even though quite an effort had been made to avoid walk by the usage of constant fraction discriminators (CFD) and by setting the thresholds on these CFDs very low, it was already known from the work of A. Bay [Bay 86] that some walk would still persists. The correction function

$$\Delta t(E) = \begin{cases} 0.0014E - 1.06 & \text{if } E > 150 \\ 0.0014E - 1.06 - 6.0 \exp(-0.042E) & \text{if } E < 150 \end{cases} \quad (4.1)$$

(E : energy in ADC channels) which corrects the time measurement of every individual bar in function of its own energy was introduced

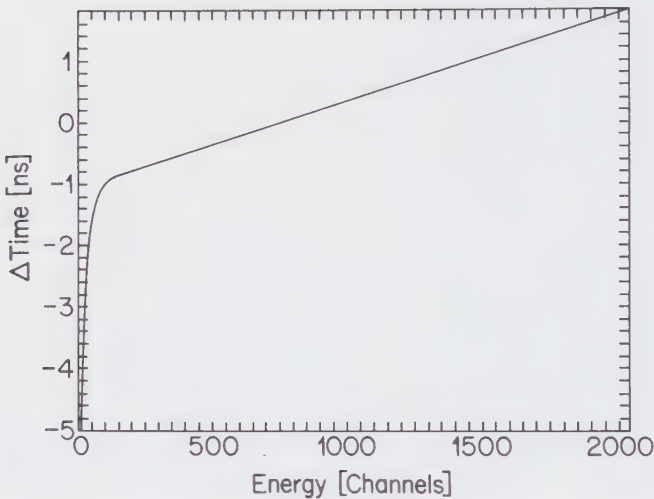


Figure 4.5: Primary walk correction function (Eq. 4.1). Depending on the energy of an individual bar, the time measurement is corrected by the corresponding value of the function.

at the stage of the raw data analysis. This function which was determined by A. Bay, is shown in Figure 4.5.

To see the effect of this correction and to check in the other time spectra the presence of walk, photons from CEX in a set of energy bands were used. Since time of flight is independent of energy for photons, any eventual variation of the “prompt peak” as a function of energy indicates the presence of walk. This search for walk is described in more detail in Appendix C and the results are tabulated and shown in diagrams. No dramatic effects were found. For the time spectrum Δt_{RF-NaI} an inverse walk has been found which can be explained as a result of the walk correction function which had been applied to the raw data analysis. For this time spectrum the walk is $\sim -1ns$ for energies between 50 MeV and 150 MeV. For the other time spectra the walk is $\sim 1ns$ in the same energy range. In all cases straight lines have been fitted through the measured points and the slope was used to calculate correction values for these time spectra during dense data analysis. Tables 4.3 and 4.4 show that

Table 4.3: Check of energy independence of asymmetry time spectrum (after correction). No walk persists in the important energy region.

Energy Range [MeV]	Average Energy [MeV]	Δt_{RF-NaI}		
		1. Peak [0.5ns/bin]	2. Peak [0.5ns/bin]	3. Peak [0.5ns/bin]
20–50	46	40.9	80.6	120.3
50–55	53	43.1	82.1	121.1
55–60	58	41.5	80.9	120.5
60–90	75	41.1	80.6	120.3
90–145	113	41.2	80.8	120.6
145–200	151	40.6	80.3	120.0
$\Delta T(20\text{--}200 \text{ MeV})$		≤ 2.5	≤ 1.8	≤ 1.1
$\Delta T(60\text{--}200 \text{ MeV})$		≤ 0.5	≤ 0.5	≤ 0.6

Table 4.4: Check of energy independence of hodoscope time spectra (after correction). No walk persists in the important energy region.

Energy Range [MeV]	Average Energy [MeV]	$\Delta t_{NaI-\mu 1}$	Δt_{NaI-H3}	Δt_{NaI-H4}	Δt_{NaI-H5}
		[0.5ns/bin]	[0.5ns/bin]	[0.5ns/bin]	[0.5ns/bin]
20–50	46	132.5	74.6	74.9	74.6
50–55	53	131.3	73.6	73.6	74.1
55–60	58	131.8	73.8	73.8	74.5
60–90	75	132.2	74.4	74.4	74.8
90–145	113	132.3	74.7	74.7	74.6
145–200	151	132.7	74.6	74.6	74.6
$\Delta T(20\text{--}200 \text{ MeV})$		≤ 1.4	≤ 1.1	≤ 1.3	≤ 0.7
$\Delta T(60\text{--}200 \text{ MeV})$		≤ 0.5	≤ 0.3	≤ 0.3	≤ 0.2

after the corrections no walk persists in the interesting energy range for any of the time spectra.

4.2.8 Time Resolution

The resolution of the time spectra can be taken from the Tables in Appendix C. The widths for Δt_{RF-NaI} and $\Delta t_{NaI-\mu 1}$ are $3.5ns$ (FWHM) and $2.5ns - 3ns$ (FWHM) for Δt_{NaI-Hi} . This width is the convolution of the burst width of the $\mu E1$ beam in pion operation mode (Sec. 3.1.2) and the time resolution of the entire detection system (detectors and electronics). With a pion burst width of $\sim 2ns$ this results in a time resolution of $\sim 2.9ns$ for Δt_{RF-NaI} and $\Delta t_{NaI-\mu 1}$ and $1.5ns - 2.2ns$ for and Δt_{NaI-Hi} .

4.3 Background

4.3.1 Bremsstrahlung

By far the biggest background arises from photons from internal and external bremsstrahlung (Sec. 2.5). For a target of the size used in this experiment the external bremsstrahlung dominates since it is proportional to the target thickness. Due to the recoil which can be taken up by the nucleus electrons from bound muon decay can have energies of up to the muon mass but the fraction of electrons with energies higher than 59 MeV is only 1.5×10^{-5} [HVR 74]. Since only 15% of all muons are decaying and since the rate of photons from bremsstrahlung decreases proportional to E_e^{-1} bremsstrahlung becomes negligible for energies of about 57 MeV. With a detector resolution of 14% we can safely consider the photon spectrum to be free of bremsstrahlung above 65 MeV.

4.3.2 Neutron Background

Since large NaI crystals are very efficient neutron detectors we had to investigate all possible sources of neutrons. In this experiment we had three sources of neutrons:

1. It is known (Sec. 2.5) that nuclear muon capture can be followed by the emission of a neutron. These neutrons represent a strong source of beam related background coming from the target.

2. Neutrons produced by muon and pion capture in the degrader and in the target surrounding metals (Fe , Cu).
3. Neutrons originating from the proton beam dump, which is located near $\mu E1$ area. Unfortunately the experimental arrangement in the $\mu E1$ area had to be such that the NaI-wall entrance window did approximately face the beam dump.

In contrast to neutrons from the first source those from the third and a part of the neutrons from the second source exhibit a strong time structure, which we will call *delayed prompt*. These neutrons are created in a strong correlation with the RF-burst. The delay with respect to prompt photons depends on their energy and will typically be in the order of a few nanoseconds. All three sources of neutrons are proportional to the number of incident particles (also the third because it is proportional to the time and to the proton beam intensity which is proportional to the muon beam intensity). Neutrons originating from the second source can be eliminated by a subtraction of the target-OUT runs from the target-IN runs. Also neutrons from the third source will be reduced by this to a large extent since the total length in time of target-IN and target-OUT runs differs only by about 2%. In any case a determination of the efficiency of our neutron suppression mechanism, explained in Section 3.4.3, is needed and if this reveals a significant number of remaining neutrons, a method for additional neutron suppression would be necessary.

Since the NaI-wall is a modular detector, neutron events and photon events can be distinguished due to their different topology in the NaI. During normal data taking when the trigger is set to γ_{conv} , the particles which are actually detected by the NaI are not photons but e^+e^- -pairs which have been produced by photons in the converter. If the trigger is set to $\gamma_{non-conv}$ then the detected particles in the NaI are photons. At these energies the photons produce in turn e^+e^- -pairs and therefore the detection mechanisms for photons and e^+e^- -pairs is the same (apart from the initial step). Photon events (or rather e^+e^- -pairs) tend to produce a widely spread shower where the radial size of the shower strongly depends on the energy of the incident photon or e^+e^- -pair. On the other hand neutrons produce knock-on

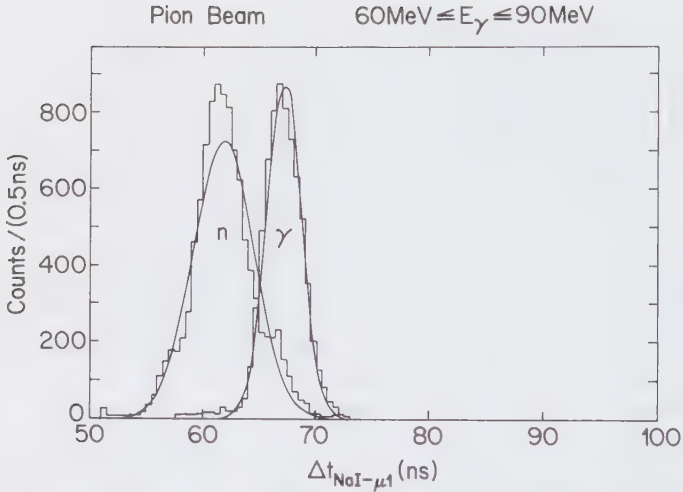


Figure 4.6: Difference in time of flight between n and γ for trigger $\gamma_{non-conv}$ from π^- on CH_2 . By requiring a time of flight of neutrons a pure neutron spectrum can be produced (time axis is reversed: slower particles appear with shorter times).

protons, which do not give rise to a shower. Therefore the number of NaI-modules (bars) participating in a photon or e^+e^- event is much bigger than for a neutron event. This fact can help us in a threefold way:

1. to determine the number of neutrons present among the normal events
2. to provide a strong tool to significantly suppress the number of neutrons
3. to produce predominantly neutron time spectra from ordinary target-IN or target-OUT runs which can subsequently be used to remove in the time spectra the neutrons remaining after the neutron suppression.

We studied the difference in topology by analyzing data from runs taken in pion operation mode, with a CH_2 target and with trigger set to either γ_{conv} or $\gamma_{non-conv}$. In the data with trigger γ_{conv} all remaining neutrons were rejected by selecting events with a time of

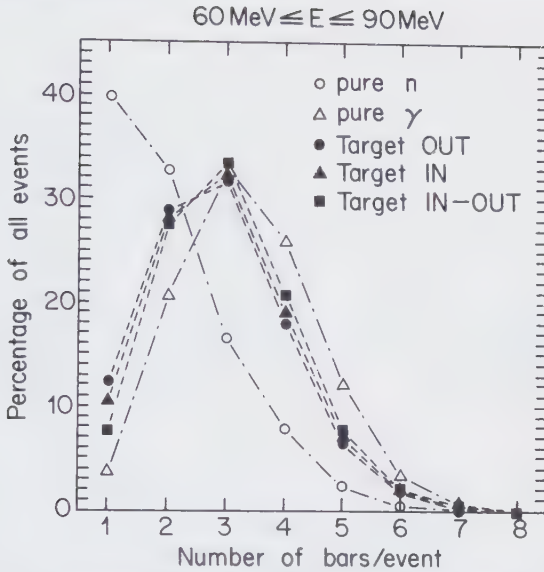


Figure 4.7: Comparison of the relative number of bars per event in the RMC energy range for pure n , pure γ and “converted photons” from RMC for target-IN, target-OUT and target IN-OUT. Clearly visible is the big difference between pure n and all other cases for 1-bar events and pure γ have almost no 1-bar events. This means that 1-bar events are almost entirely n . Also some of the 1-bars for target-IN vanish for target IN-OUT (neutrons of source type two and partially three) and target-OUT is bigger than target-IN.

flight of photons and in the data with trigger $\gamma_{non-conv}$ the photons were rejected by selecting events with a time of flight of neutrons (Fig. 4.6). With these data it is possible to study number of bars per event for pure photon and pure neutron events and compare them with those of RMC photons for target-IN, target-OUT and target IN-OUT in normal muon operation mode. The result of this study is shown in Figure 4.7 and the numbers are compiled in Table D.1. The energy dependence is shown in figures 4.8 and 4.9. The average number of bars per events remains quite independent of the energy for neutrons while it varies for photons, as shown in Figure 4.10 (the numbers are compiled in Table D.2). A first method to exploit this fact is to accept only events which have more than one bar per event (1-bar cut) or only those which have more than two bars

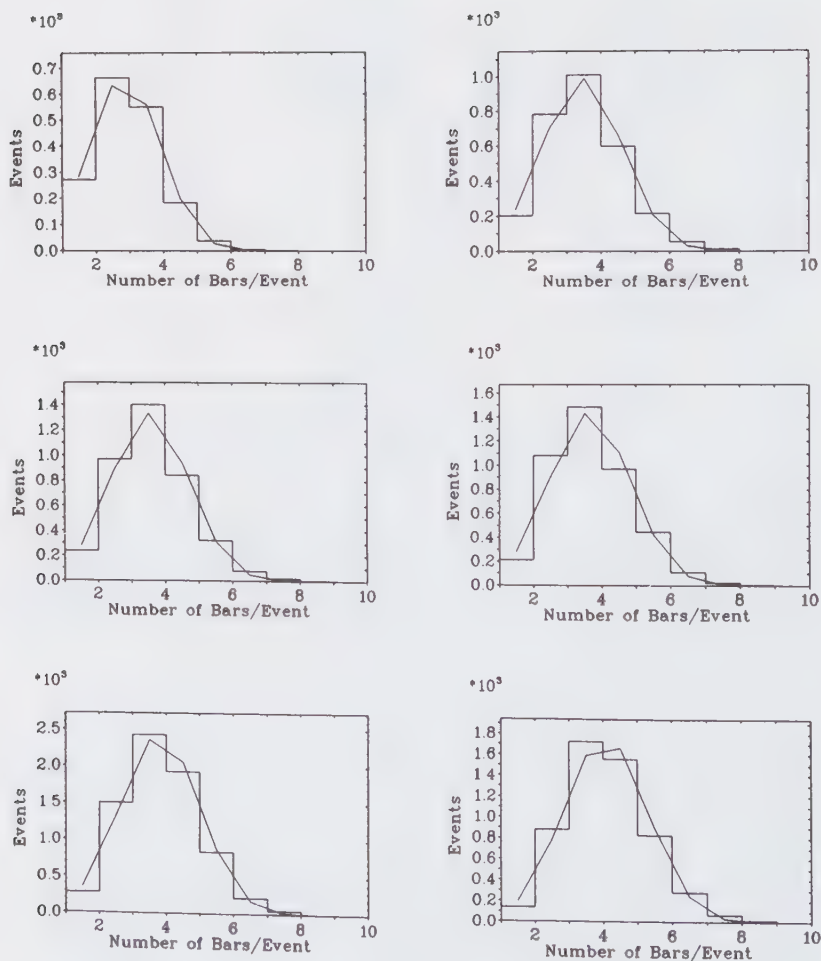


Figure 4.8: Number of bars per γ for energies between 40 MeV and 100 MeV in energy bands of 10 MeV.

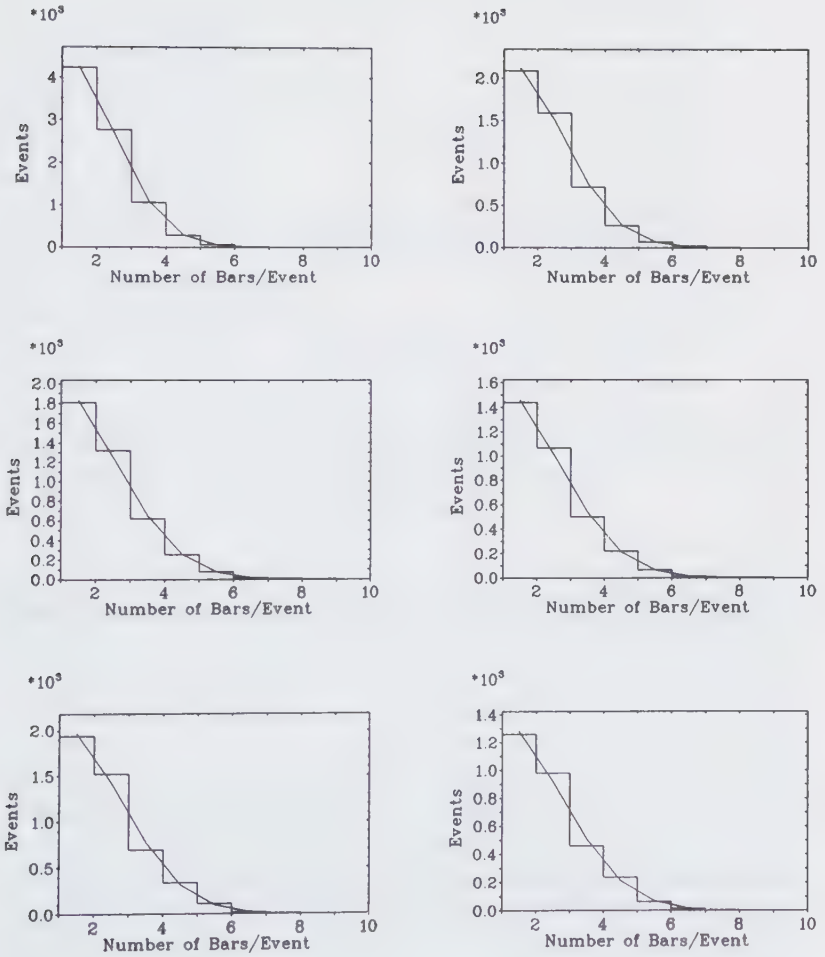


Figure 4.9: Number of bars per n for energies between 40 MeV and 100 MeV in energy bands of 10 MeV.

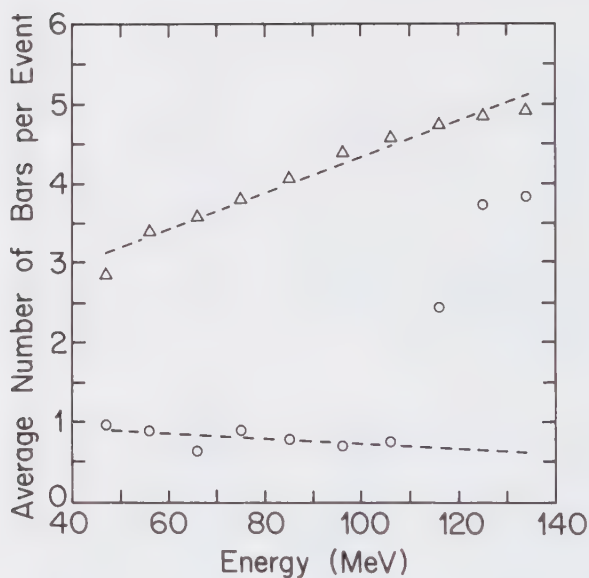


Figure 4.10: Energy dependence of average number of bars per event for γ (triangles) and n (circles). The time of flight cut does not anymore suppress the photons in the neutron sample for energies higher than 110 MeV.

Table 4.5: Summary n reduction due to cuts on number of bars per event.

Energy Range [MeV]	Cut on 1. bar/event		Cut on 1.&2. bar/event	
	% of n lost	% of γ lost	% of n lost	% of γ lost
60 – 65	44.1	6.1	76.2	31.2
65 – 70	43.5	4.9	75.7	29.8
70 – 80	41.9	3.8	74.8	24.5
80 – 90	41.6	2.5	74.0	18.5

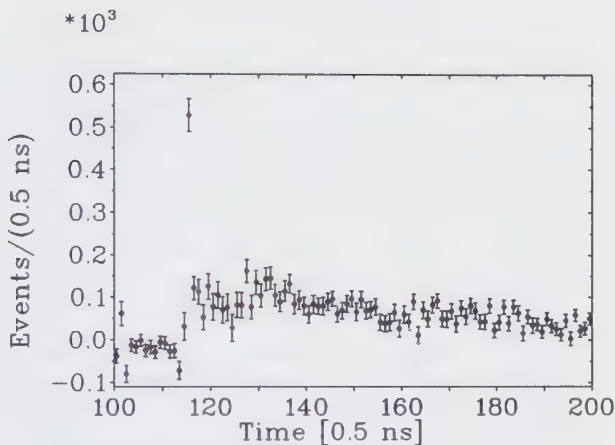


Figure 4.11: Time spectrum $\Delta t_{NaI-\mu 1}$ for 1-bar events (neutrons) from the target in the energy range 60 MeV–90 MeV. The prompt neutrons have vanished entirely.

per event (1&2-bars cut). Table 4.5 shows that we can get rid of more than 40% of all neutrons at a loss of only 6%–3% photons for a 1-bar cut and about 75% of all neutrons at a loss of 31%–19% photons for a 1&2-bar cut. On the other hand we can create almost pure n time spectra from a muon run by accepting only 1-bar events. Such time spectra are shown in figures D.1, D.2. The contribution from (delayed) prompt which is present in these figures vanishes entirely for the signal from the target shown in Figure 4.11. The exponential shape of the energy spectrum for 1-bar events which is shown in Figure 4.12 is in agreement with measurements of the energy spectrum for neutrons emitted after ordinary muon capture on ^{40}Ca performed by van der Pluym et al. [vdP+ 86].

To determine the ratio of N_n/N_γ a fit of the superpositions of pure n and pure γ number of bars per event to those of muon capture can be made. The fitted parameters are the relative contributions of the respective number of bar per event spectra. The result of these fits is compiled in Table 4.6. At the high energy end the neutron

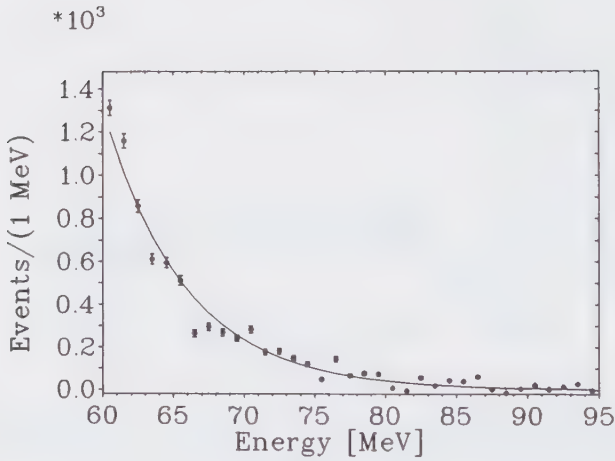


Figure 4.12: Energy spectrum of 1-bar events. Superimposed is an exponential fit to the spectrum.

Table 4.6: Summary of n background.

Energy Range [MeV]	N_n/N_γ		
	Target-IN	Target-OUT	Target IN-OUT
55 – 60	0.21 ± 0.02	0.21 ± 0.01	0.19 ± 0.01
60 – 65	0.15 ± 0.02	0.17 ± 0.01	0.11 ± 0.01
65 – 70	0.16 ± 0.01	0.23 ± 0.01	0.08 ± 0.01
70 – 80	0.23 ± 0.01	0.43 ± 0.01	0.07 ± 0.01
80 – 90	0.25 ± 0.01	0.48 ± 0.02	0.01 ± 0.01
90 – 145	0.19 ± 0.01	0.31 ± 0.01	0.03 ± 0.01

Table 4.7: Summary of n background with cut on number of bars per event.

Energy Range [MeV]	N_n/N_γ after Cut on Number of Bars/Event					
	Target-IN		Target-OUT		Target IN-OUT	
	> 1 Bar	> 2 Bar	> 1 Bar	> 2 Bar	> 1 Bar	> 2 Bar
60 – 65	0.084	0.036	0.095	0.040	0.066	0.030
65 – 70	0.090	0.039	0.130	0.056	0.048	0.022
70 – 80	0.134	0.058	0.250	0.125	0.042	0.019
80 – 90	0.146	0.065	0.280	0.125	0.006	0.003

contribution is significantly higher for target-OUT than for target-IN while almost no neutrons remain in the target IN-OUT spectra. The remaining fraction of neutrons after a 1-bar or 1&2-bar cut is compiled in Table 4.7. The dense data analysis was done in four different ways:

1. A good event must have only one bar (1-bar event)
2. A good event must have a number of bars ≥ 2 (1 bar cut).
3. A good event must have a number of bars ≥ 3 (1&2 bar cut).
4. A good event must have a number of bars ≥ 2 and the remaining neutrons are removed by subtracting an appropriately normalized time spectrum of 1-bar events (Table 4.7).

4.3.3 Pion Induced Background

As explained in Section 3.1 there is a small but important π^- contamination in the beam. These pions produce photons via the radiative pion capture (RPC) process in ^{40}Ca

$$\pi^- \text{ } ^{40}\text{Ca} \rightarrow \gamma \text{ } ^{40}\text{K}$$

which gives rise to a background extending over the entire RMC spectrum up to the pion mass with a peak around 115 MeV. With a branching ratio of $(1.94 \pm 0.35)\%$ [BCT 77] and a pion contamination of $\simeq 5 \times 10^{-4}$ the background rate is of the same order of magnitude as the RMC process.

As the π^- are very short lived ($\approx 10^{-12}ns$) in comparison with μ^- in ^{40}Ca ($\approx 340ns$) the pion induced photons have a very strong correlation with the RF signal from the accelerator. The existence of high energy photons with $E_\gamma > E_{RMC}^{max}$ and the presence of a very clear peak in time spectra of photons with $E_\gamma > m_\mu/2$ manifest the existence of this background. Although undesired as strong background for the RMC process these pion induced photons provide a very easy way of monitoring the time calibrations and to thereby detect any long-term variation of the time calibrations. In Figure 4.13 the hodoscope time spectra are shown. The prompt peaks originating from the pion induced photons are visible in all the six spectra, but most clearly in the outer hodoscopes (Δt_{NaI-H1} , Δt_{NaI-H2} and Δt_{NaI-H6}), indicating that pions are predominately found in the muon beam halo. The number of the prompt photons can be determined from the area under these peaks. This procedure is illustrated in Figure 4.14. We used the summed hodoscope time spectra, rather than the individual strips because of the higher accuracy with which the prompt contribution can be determined in this manner. The fact that not all of the high energy photons fall into the prompt region indicates that a small fraction of the pion induced events escaped our prompt tagging. For a typical run this fraction is 15% and the number of pion induced photons determined in the above way had to be corrected for this deficiency.

4.3.4 Cosmic Background

Cosmic muon background pertaining our cosmic veto logic was determined by a run with normal experimental conditions but no beam in the the experimental area. The yield of cosmic background is ~ 0.2 events/sec for events of all energies but only $\sim 10\%$ of these events lie in the important energy range of 60–90 MeV. This background is strictly proportional to the time and the target IN and target OUT times are almost equal ($\sim 2\%$). The cosmic background is therefore about a factor of 1000 below the RMC rate and can thus be neglected.

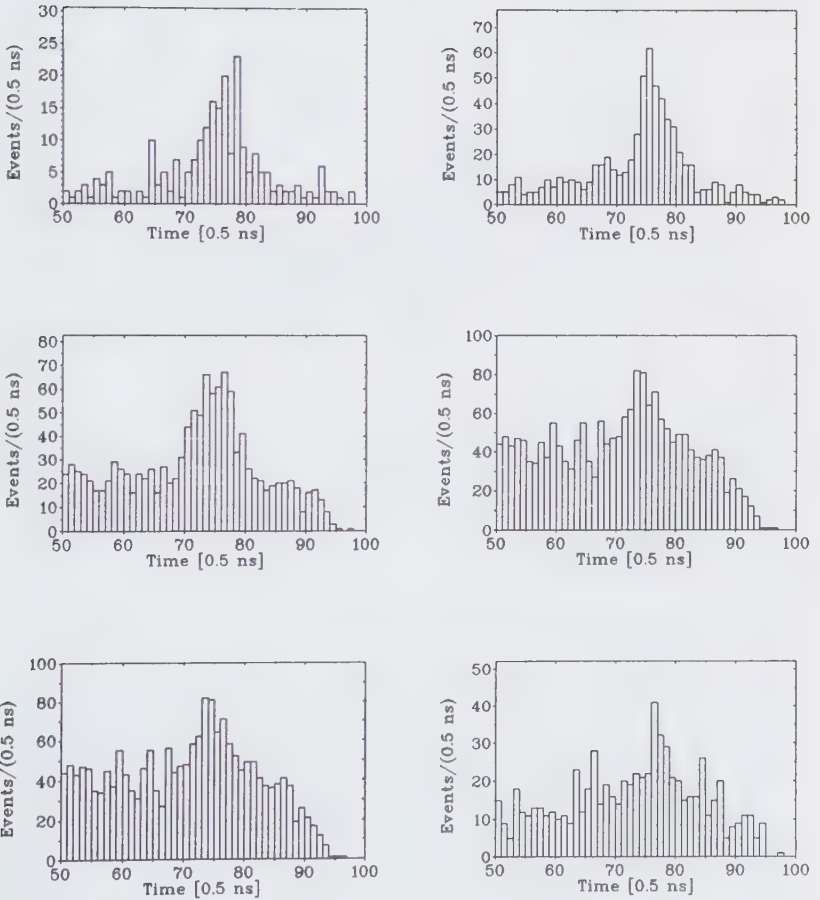


Figure 4.13: Hodoscope time spectra with events in the RMC energy range of a typical run.

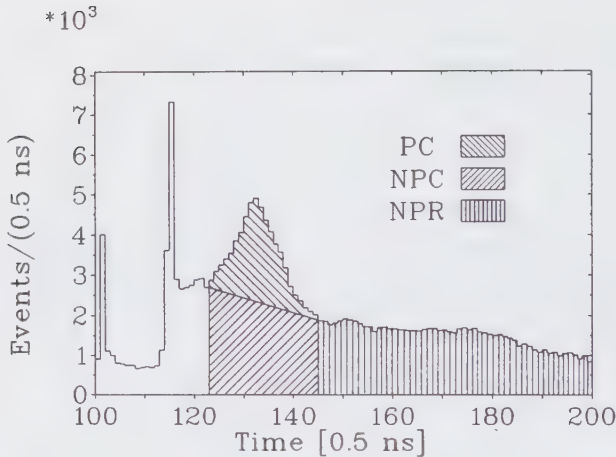


Figure 4.14: Typical time spectrum $\Delta t_{NaI-\mu 1}$. PC: (pion induced) prompt contribution, NPC: muon contribution falling into the prompt region (non-prompt contribution), NPR: (non-prompt) muon region.

4.4 Gamma Runs

4.4.1 Monitoring of Time Calibration

It was considered necessary to monitor the time calibration over the whole three weeks duration of the experiment since an eventual variation of the time calibration leads to a deterioration of the time resolution of the sum time-spectra.

The presence of the π^- background in the beam which is otherwise undesired gives rise to a narrow line in the time spectra via the instantaneously (prompt) occurring process $\pi^- p \rightarrow \gamma n$. This background is strong enough to make this narrow line clearly visible for photons with $E_\gamma > E_{RMC}^{max}$ and thus can serve as a very nice “built-in” calibration line.

For this monitoring of the time calibration the high energy photons with $90 \text{ MeV} \leq E_\gamma \leq 145 \text{ MeV}$ were selected. The position of the calibration line was found by fitting a gaussian onto it. Figure 4.15

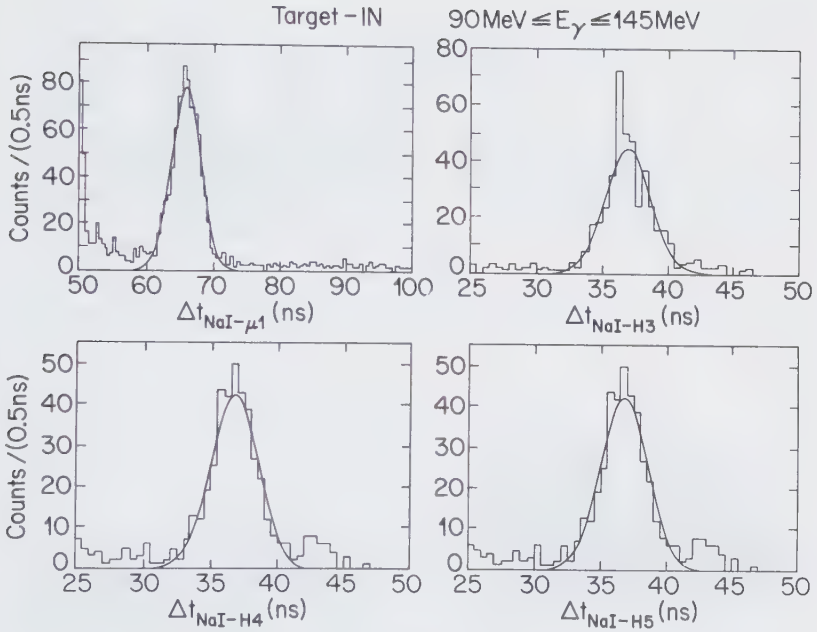


Figure 4.15: Typical high energy time spectra of $\Delta t_{NaI-\mu 1}$ and Δt_{NaI-Hn} .

shows typical spectra with their fitted gaussians. This was done for the time spectra $\Delta t_{NaI-\mu 1}$, Δt_{NaI-H3} , Δt_{NaI-H4} , Δt_{NaI-H5} ² and for the three lines in Δt_{RF-NaI} for all the γ target-IN and target-OUT runs. The results of these fits are given in the tables and diagrams in Appendix B. No dramatic variations of the time calibrations have been found in any of the time spectra: the offsets of the individual runs were less than $1.5ns$. For each run an offset correction for the peak mean position was calculated and introduced in a subsequent analysis of this run.

²The calibrations of Δt_{NaI-H1} , Δt_{NaI-H2} and Δt_{NaI-H6} were not monitored since (as explained in Section 4.3) they will not be used any further.

Table 4.8: Measured prompt peak positions of the sum time spectra before and after correction.

Target	Δt_{RF-NaI}		$\Delta t_{NaI-\mu 1}$	Δt_{NaI-H3}	Δt_{NaI-H4}	Δt_{NaI-H5}
IN						
uncorrected	57.48	97.05	134.18	78.54	80.61	80.61
	± 0.08	± 0.08	± 0.02	± 0.02	± 0.03	± 0.03
corrected	58.43	97.99	132.25	74.60	72.46	72.46
	± 0.08	± 0.08	± 0.02	± 0.03	± 0.13	± 0.13
OUT						
uncorrected	56.3	96.1	134.30	78.78	80.87	80.87
	± 0.2	± 0.1	± 0.04	± 0.04	± 0.05	± 0.05
corrected	58.6	98.4	132.25	73.7	71.2	71.6
	± 0.1	± 0.1	± 0.04	± 0.1	± 0.3	± 0.3

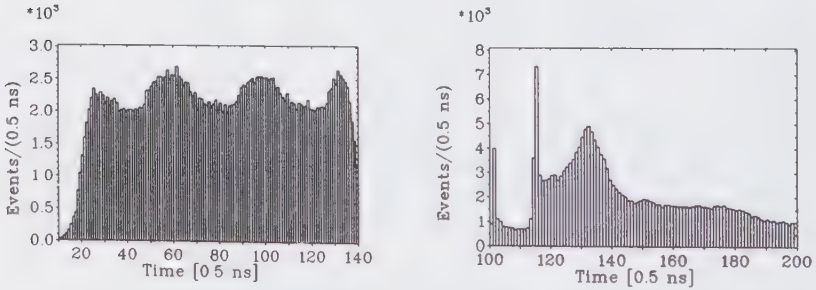


Figure 4.16: Initial time spectra Δt_{RF-NaI} and $\Delta t_{NaI-\mu 1}$ of RMC photons. The prompt structure from pion induced photons is clearly visible in both histograms.

4.5 Prompt Subtraction

A raw time spectrum of photons in the RMC energy region contains always a strong contribution from pion induced photons (*prompts*). As can be seen in Figure 4.16, the presence of these prompts makes a determination of the muon-spin photon asymmetry entirely impossible. Figure 4.13 already shows that the prompt contribution varies strongly among the six hodoscope stripes. For a typical individual run stripes H1 and H2 contain together 30% and stripe H6 contains 20% of all prompts but only 8% and 7% respectively of all events

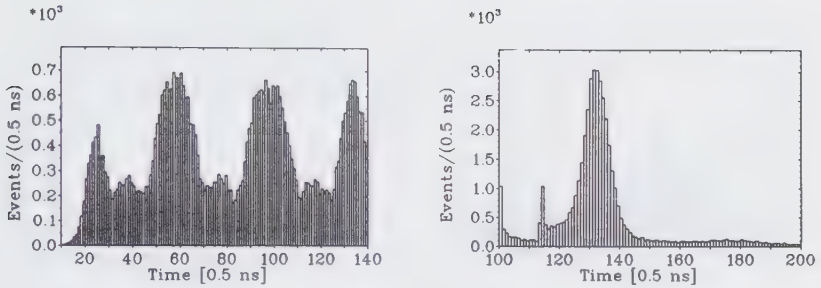


Figure 4.17: Pure prompt time spectra: Δt_{RF-NaI} (left) and Δt_{RF-NaI} (right).

(most of which are prompts). Therefore we decided to require for a good event to come from neither H1, H2 or H6.

The basic idea to get rid of the prompts is to determine the number of prompts present in the RMC energy range and to subtract the respective fraction of “pure prompt” spectra from the spectra in the RMC energy range. The “pure prompt” spectra can be obtained from high energy photons, which are produced exclusively by pions. This method relies on the fact that the time distribution of the photons is independent of their energy if all eventual energy-time correlation as introduced by electronics is removed (Sec. 4.2.7). Therefore an accurate determination of the number of prompts present in the RMC energy region is required i.e. the borderline between prompt contribution (*PC*) and non-prompt contribution (*NPC*) as shown in Figure 4.14 has to be found. A straightforward way to do this, is to fit an exponential to the non-prompt region in the time spectrum $\Delta t_{NaI-\mu 1}$ as shown in Figure 4.18. Apparently these time spectra do not have a pure exponential shape and therefore this method of determination of the prompt contribution is not very reliable. Instead we subtract from the time spectrum shown in Figure 4.18 (left) the time spectrum shown in Figure 4.18 (right) normalized to both sides of the peak (NPR in Figure 4.14). This subtraction results in a time spectrum whose number of events in the prompt region is the exact number of events in the prompt contribution of the RMC time spec-

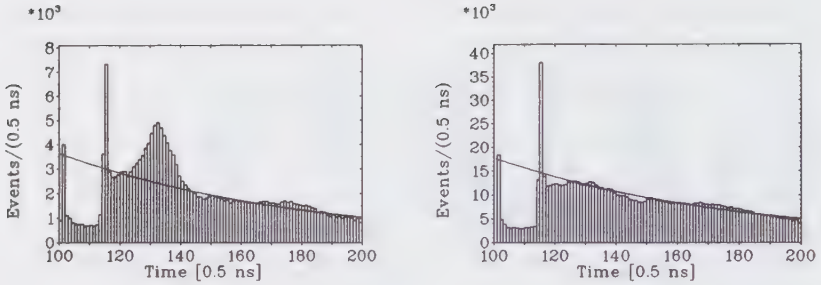


Figure 4.18: Time spectrum $\Delta t_{NaI-\mu 1}$ for RMC (left) and bremsstrahlung (right) energy range. Superimposed is an exponential fitted in the muon region (channels 145–200).

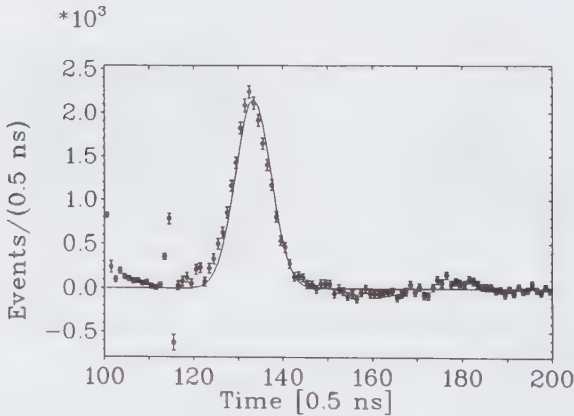


Figure 4.19: Time spectrum $\Delta t_{NaI-\mu 1}$ in the RMC energy region for the prompt contribution only. The mean of the superimposed gaussian shows that the peak has the correct “prompt time” (within 1/4 ns).

trum in Figure 4.18 (left). Figure 4.19 shows this time spectrum. The prompt contribution to both of the time spectra in Figure 4.16 can be removed by subtraction of the respective pure prompt time spectra (Figure 4.17) normalized to the integral number of events in

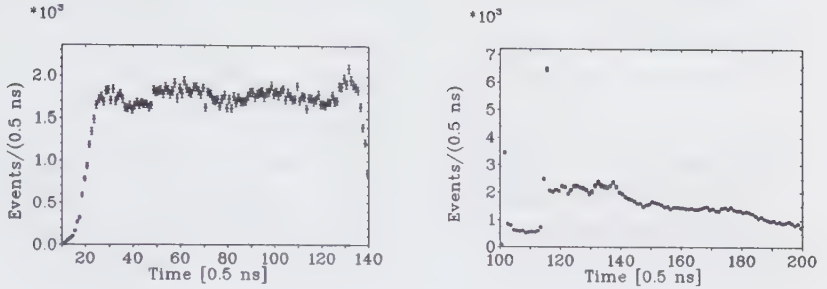


Figure 4.20: Time spectra Δt_{RF-NaI} (left) and Δt_{RF-NaI} (right) after prompt subtraction.

the prompt contribution (Figure 4.19) and the resulting time spectra are shown in Figure 4.20. Since the prompt contribution is not the same for target IN and target OUT this determination of the prompt contribution and its subtraction has to be done separately for target IN and for target OUT. Moreover the entire procedure is done individually in each of the four energy bands in the RMC energy range (60 MeV–65 MeV, 65 MeV–70 MeV, 70 MeV–80 MeV, 80 MeV–90 MeV). To study the effect of the neutron contamination all of this is done for an analysis with number of bars per event ≥ 2 and ≥ 3 respectively. Also one pass of the analysis is made with a subtraction of the remaining neutrons prior to subtraction of prompts and target IN-OUT.

4.6 Asymmetry Fit

The function which has to be fitted to the data can be written as

$$N(t_j) = N \cdot \exp(-(t_j - t_0)/\tau)(1 + \alpha \cos(\omega(t_j - t_0) + \phi)) \quad (4.2)$$

where t_0 denotes the arrival of the muon burst and α the experimentally measurable asymmetry. The μ^- arrive with backward oriented spin, the detector is set up at 90° or 270° and therefore $\phi = \pm\pi/2$ and can be absorbed by writing a sine instead of a cosine.

By extracting t_0 from the exponential function the above equation can be written as

$$N(t_j) = N_0(t_0, \tau) \cdot \exp(-t_j/\tau)(1 + \alpha \sin(\omega t_j - \omega t_0)) \quad (4.3)$$

with $N_0(t_0, \tau) = N \exp(t_0/\tau)$. The parameters N_0, t_0 and α have to be determined by fitting the function 4.3 on the experimental data.

A new μ^- -bunch arrives every $20ns$ and brings the exponential decay part of function 4.3 back to its original value. The muon burst has a finite width in time with an approximately gaussian shape. The width of this gaussian was experimentally determined to be $\Delta t(FWHM) = (5.5 \pm 0.3)ns$. The function which is used for the fit is folded with a gaussian having the time-width of the muon burst. For the actual fitting the function minimization program *MINUIT* [JaR 78] was used. The fitting procedure is based on a minimization of the χ^2 function defined as

$$\chi^2 = \sum_i \frac{[N_{exp}(i) - N_{theo}(i)]^2}{\sigma^2(i)} \quad (4.4)$$

where the $N_{exp}(i)$ are the counts in channel i of the TDC, $N_{theo}(i)$ is given by Eq. 4.3 and $\sigma(i)$ represents the expected variance which is for high and statistically distributed count rates of independent events $\sigma^2(i) = N_{theo}(i)$.

4.7 Asymmetry Calibration

Unfortunately the theoretical asymmetry Γ_γ (Eq. 2.14) is not directly accessible by the experiment. Several effects are present in the experiment which all tend to reduce the measurable asymmetry α . The experimental and the theoretical asymmetry are related by $\alpha = P_\mu \cdot \Gamma_\gamma$, where P_μ denotes the magnitude of the residual μ^- polarization in the ground state of the muonic atom. The magnitude of P_μ is given by the product of the various effects which contribute to a reduction of the residual polarization P_{μ^-} :

Beam polarization P_B Muon beams produced from pion decay undergo a kinematical depolarization. The muon beam from SIN muon channel I has a beam polarization of about 0.7 (Table 3.1).

Depolarization D_{μ^-} The muon is depolarized during the cascade down to the $1s$ -state. For a spinless nucleus the residual polarization is only $\simeq 1/6$ of the initial and for ^{40}Ca $D_{\mu^-} = 0.14 \pm 0.01$ have been measured [Evs 75, Sch 82].

Time width of the muon bunch The arriving muon bunch has a finite width in time which is mainly due to pions decaying at different times during their travel in the muon channel. Muons which arrive slightly out of time with respect to RF also precess slightly out of phase with respect to the other muons in the target and therefore reduce the average polarization of the muons in the target. The time width of the muon bunch has been measured and is taken into account (Sec. 4.6).

Imprecise resonance frequency A badly adjusted magnetic field or an inhomogeneous field can also causes a decrease of the average polarization. Since the resonance is rather broad this is not an important effect.

Finite time resolution of the detector system The time resolution of the detector system is $\simeq 2ns$. The effect of this on the measurable asymmetry is very small.

Chapter 5

Results and Discussion

5.1 Electron Asymmetry

The electron asymmetry fit was made in the energy range between the low energy electronic cutoff of 40 MeV and 50 MeV. Due to boundary effects in the time spectrum the fit had to be limited to two periods which included about 486×10^3 events. The results of this fit are $\alpha_{e^-} = -0.0665 \pm 0.005$ (8.0%) and $t_0 = 0.3 \pm 0.2$. This result is consistent with the asymmetry fit of photons from bremsstrahlung for which the corresponding fit in the same energy range, for the same t_0 and for 150×10^3 events yields $\alpha_{\gamma-brems} = 0.060 \pm 0.013$ (22%). Figures 5.1 and 5.2 show the fitted electron and bremsstrahlung time spectra respectively.

With the measured electrons asymmetry the residual polarization P_μ can be determined to be

$$P_\mu = \frac{\alpha_{e^-}}{M_{e^-}C} = 0.104 \pm 0.008 \text{ (8.0\%)} \quad (5.1)$$

where $M_{e^-}C$ is the calculated average decay electron in the respective energy range ($M_{e^-} = -1/3$, $C(40 - 50 \text{ MeV}) = 1.914$).

5.2 Photon Asymmetry

Asymmetry time spectra from three different conditions of analysis were fitted: events with more than one bar and no additional neutron subtraction, events with more than two bars and no additional neutron subtraction and events with more than one bar and

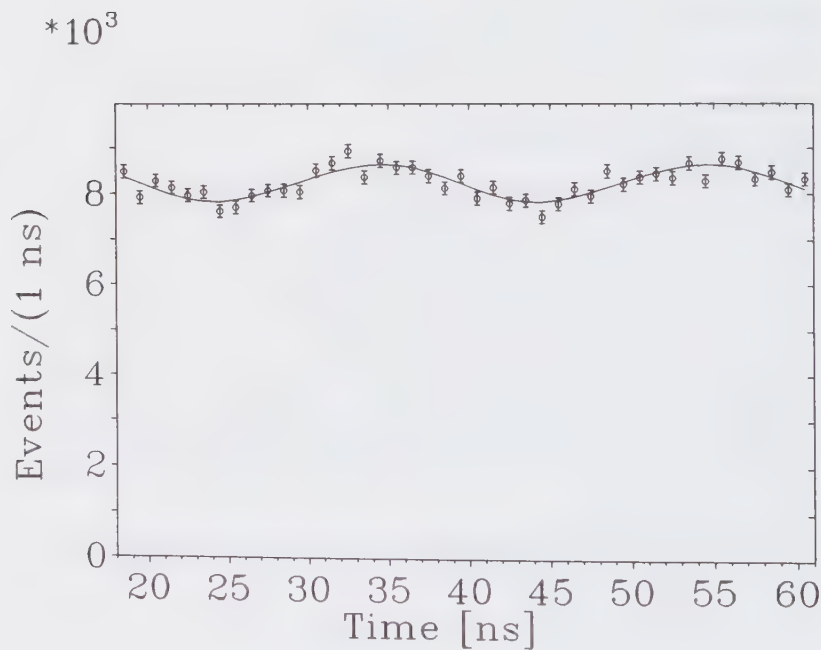


Figure 5.1: Fit to the electron time spectrum. ($\alpha_{e^-} = -0.0665 \pm 0.005$ (8.0%), $t_0 = 0.3 \pm 0.2$).

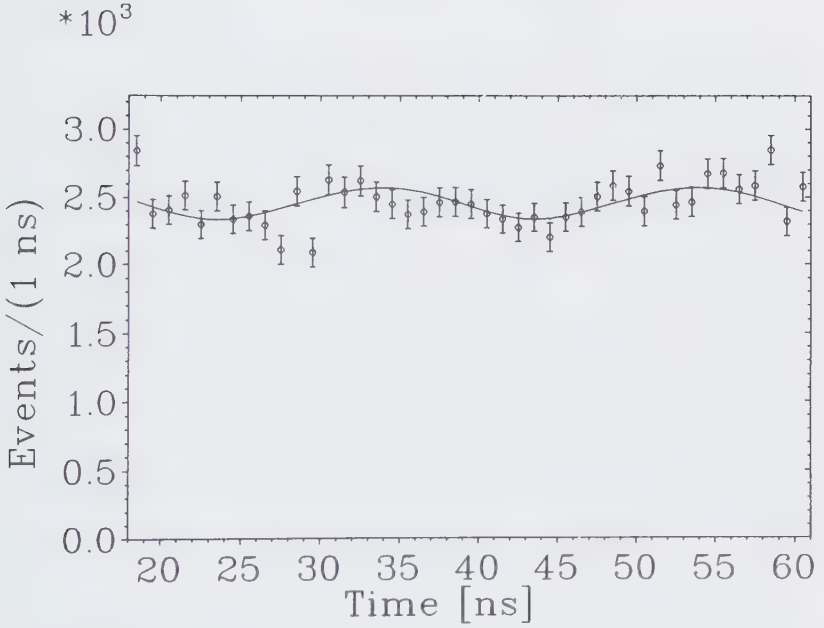


Figure 5.2: Fit to the time spectrum of bremsstrahlung photons ($\alpha_{\gamma\text{-brems}} = 0.060 \pm 0.013$ (22\%)).

Table 5.1: Summary of photon asymmetry fits. The percentages of remaining neutrons are taken from Table 4.7.

Number of Bars/Event	Neutron Subtraction	Remaining n	Number of events (10^4)	Asymmetry α_γ
> 1	without	$\leq 5\%$	2.8	0.098 ± 0.012
> 2	without	$\leq 2\%$	2.0	0.100 ± 0.015
> 1	with	≈ 0	2.7	0.081 ± 0.013

additional neutron subtraction. For the fit of the RMC photon time spectrum, t_0 is fixed to the value from the electron asymmetry fit. Events from the energy range 65–80 MeV are used for the fit and the results for the three conditions of analysis are summarized in Table 5.1. Figure 5.3 shows the result of the photon asymmetry fit. The fits yield asymmetry values which are compatible within their errors and no systematic effect from remaining neutrons is visible. Since the asymmetry of neutrons in this energy range is negative remaining neutrons should decrease the values for the asymmetry which is not the case here. Because it has the smallest error and a slightly better χ^2 per degree of freedom we use the first asymmetry value of $\alpha_\gamma = 0.098 \pm 0.012$ (12.2%). With the value of the residual polarization P_μ from Equation 5.1 the theoretical asymmetry $\overline{\Gamma}_\gamma$ can be determined

$$\overline{\Gamma}_\gamma = \alpha_\gamma / P = 0.94 \pm 0.14 \text{ (15\%)} \quad (5.2)$$

This value of $\overline{\Gamma}_\gamma$ is in agreement with the previous measurements except the one of di Lella [DHR 71] and its precision is much better than that of any previous measurement. The average of the asymmetry parameter over the values of Table 1.1 without the value of di Lella et al. and including the above value from the present work yields

$$\overline{\Gamma}_\gamma = 0.91 \pm 0.10 \text{ (11\%)} . \quad (5.3)$$

For the calculation of this average we have modified the published preliminary result of Hasinoff et al. using the measured value of the depolarization (Sec 4.7) instead of the theoretical value (with no error) used by them. A fit to photons in the energy range 60–65 MeV

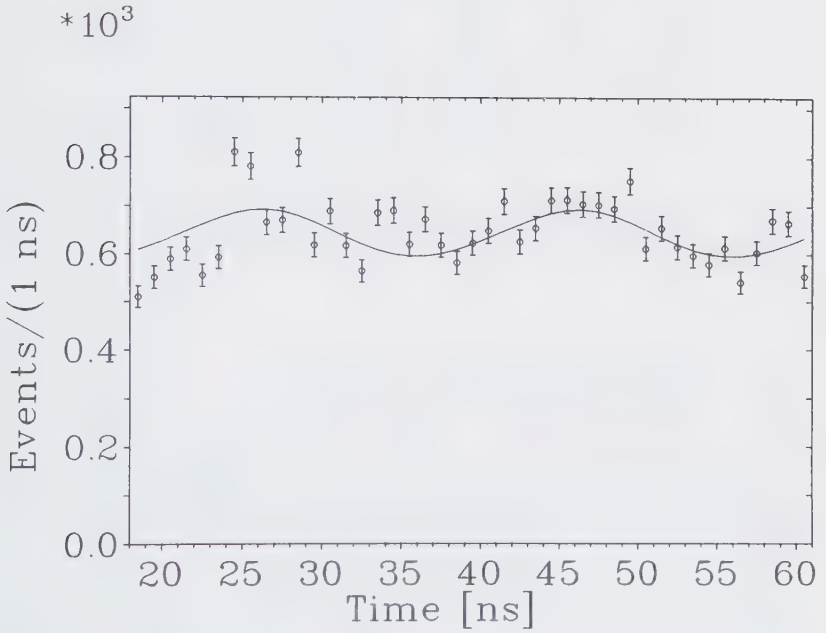


Figure 5.3: Fit to the time spectrum of RMC photons in the energy range 65–80 MeV ($\alpha_\gamma = 0.098 \pm 0.012$ (12.2%)).

Table 5.2: Predictions of muon-spin photon asymmetry coefficient $\Gamma(k)$ for RMC on ^{40}Ca as a function of photon energy k (from [GKO 87]).

k [MeV]	$\Gamma(k)$		
	$g_P = 4.5$	$g_P = 7.5$	$g_P = 12.0$
57	0.966	0.924	0.830
65	0.959	0.907	0.801
73	0.950	0.887	0.768
81	0.939	0.862	0.724
89	0.928	0.831	0.659

yields a negative value of $\alpha = -0.030 \pm 0.024$ for the asymmetry due to a contribution of bremsstrahlung to the RMC photons.

5.3 Comparison with Theory

For the determination of the induced pseudoscalar coupling constant g_P from the measured averaged photon asymmetry $\overline{\Gamma}_\gamma$ recent calculations from Gmitro [GKO 87] have been used. For these calculations Gmitro used a modified impulse approximation (MIA) scheme [GKO 84]. The modified impulse approximation scheme which has been derived by Gmitro et al. [Gmi+ 86] is an extension to the microscopic calculation (impulse approximation) [Gmi+ 81] taking into account the constraints dictated by the electromagnetic current continuity equation. The overestimation of the photon yield in the impulse approximation in comparison with the phenomenological model calculations of Christillin [Chr 81, CG 85] and with experiments [Fri+ 85, Doe 87] disappears with the conservation of the electromagnetic current and the two model calculations come into mutual agreement. The resulting values for the photon asymmetry Γ , which are given in Table 5.2 and plotted in Figure 5.4, are by 10–15% higher than the older values calculated with impulse approximation (IA).

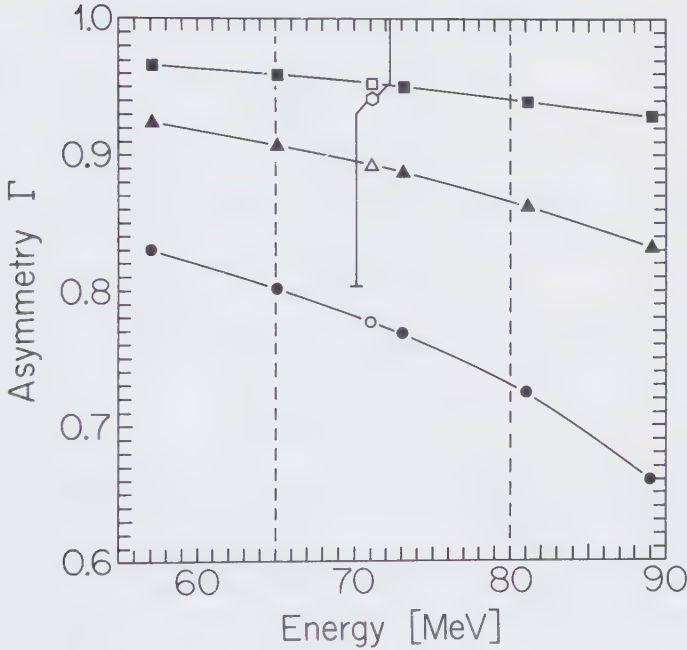


Figure 5.4: Predicted values of Γ_γ for the three values of g_P as a function of energy (squares: $g_P/g_A = 4.5$, triangles: $g_P/g_A = 7.5$, circles: $g_P/g_A = 12$). The black marks show the values of Table 5.2, the curve between the points is a linear interpolation. The dashed lines mark the averaging interval 65-80 MeV and the open marks show the predicted asymmetry $\bar{\Gamma}_\gamma$ for the three values of g_P (from Table 5.3). The hexagon with the error bar represents the asymmetry parameter Γ_γ as determined in this work (Eq. 5.2).

5.4 Determination of g_P

To be able to compare the experimentally determined averaged asymmetry $\bar{\Gamma}_\gamma$ with the theoretical predictions for Γ_γ for the three values of g_P , the theoretical values for Γ_γ have to be averaged over the

Table 5.3: Averaged asymmetry $\overline{\Gamma}_\gamma$ for three values of g_P .

g_P/g_A	$\overline{\Gamma}_\gamma$ 65–80 MeV
4.5	0.952
7.5	0.892
12.0	0.775

measured experimental spectrum in the following way:

$$\overline{\Gamma}_\gamma = \frac{\int R(k) \Gamma_\gamma(k) \cdot dk}{\int R(k) \cdot dk} \quad (5.4)$$

The corresponding averaged energy $\bar{k}$ is calculated as

$$\bar{k} = \frac{\int R(k) k \cdot dk}{\int R(k) \cdot dk} \quad (5.5)$$

of 65 MeV and 80 MeV as the lower and upper boundaries for the integral respectively. Table 5.3 gives the resulting averaged asymmetries. Figure 5.5 shows a comparison of the predicted asymmetries Γ_γ for the three values of g_P , the averaged asymmetries $\overline{\Gamma}_\gamma$ and the experimental result. From a linear interpolation in Table 5.3 we deduced for g_P a value of $g_P = (5.1^{+4.4}_{-7.0})g_A$. The resulting value of g_P is consistent with the absence of a pseudoscalar coupling ($g_P = 0$) as well as with the Goldberger-Treiman value ($g_P = 7g_A$). While there was little difference in the predicted values of the asymmetry parameter Γ_γ for the older calculations like shell model and phenomenological nuclear response calculation there seems to be a significant difference to the newer modified impulse approximation. Figure 5.5 shows a comparison of the the predictions for these three model calculations. The modified impulse approximation which seems to be very successful in predicting the RMC branching rates [Doe 87], unfortunately predicts a lesser sensitivity of the asymmetry parameter Γ_γ to the induced pseudoscalar coupling g_P .

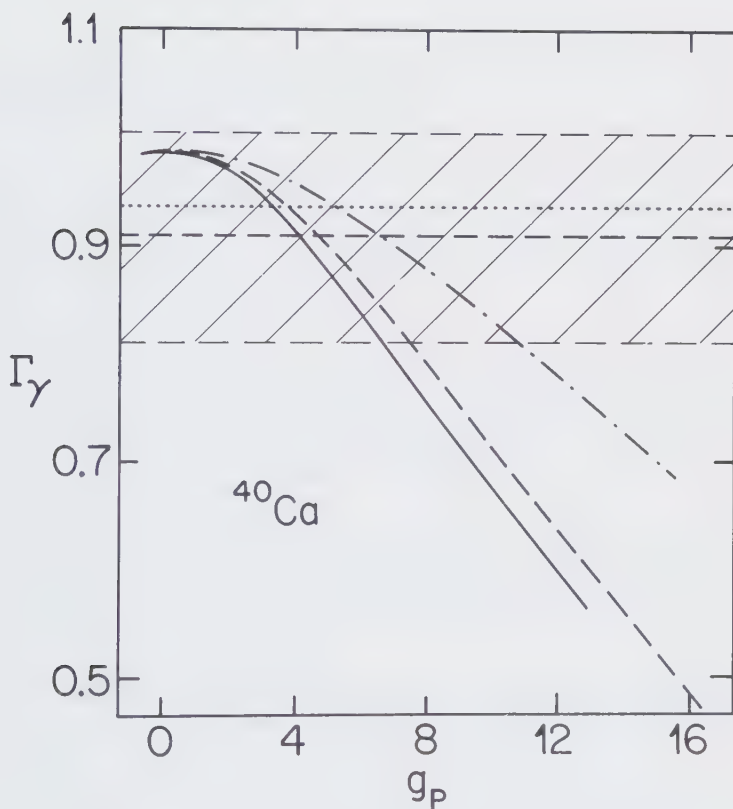


Figure 5.5: Asymmetry parameter Γ_γ as a function of the induced pseudoscalar coupling for three model calculations. Solid line: shell model [Gmi+ 81] (IA), dashed line: phenomenological model [Chr 82, Chr 81], dashed-dotted line: shell model [GKO 87] (MIA). The dotted line shows the value of Γ_γ as determined in this work. The cross-hatched area with the dashed line in its center represents the world average of the asymmetry parameter Γ_γ with its error.

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Appendix A

The SIN-NaI

The data taken with the SIN-NaI detector system (the right-hand detector system shown in Figure 3.1) is not used in this work. Because of the much lower statistics ($\simeq 1/3$) of solid angle, is it not possible to perform the prompt subtraction procedure described in this work with sufficient precision. Also, due to the fact that the SIN-NaI is a single crystal, the method which was used to account for the neutron background can not be used. The detector system is described here only for completeness and consists essentially of the following elements:

1. two consecutive plastic scintillators used as charged particle anticounters.
2. an active NaI(Tl) converter to convert photons into e^+e^- -pairs.
3. a plastic Čerenkov counter to tag e^+e^- -pairs.
4. a large cylindrical one-crystal NaI(Tl).

The whole detection system is encased by a box of shielding material against charged background and neutrons. This shielding consists of an outmost layer of 20cm borated polyethylene, a thin foil of *Cd* and a 10cm layer of *Pb*. Inside this shielding box is a box of large plastic scintillators surrounding the NaI crystal which are used to veto the passage of charged particles like cosmics, charged particles from *n*-capture in *Cd* and also to detect those particles which start in the crystal close to the boundary such that they lose a significant amount of their shower out of the crystal.

The front shielding consists only of 10cm *Pb*. The entrance window in the lead is covered on both sides with a plastic scintillator (AC11 and AC12) as charged particles anticounter. This double anticounter system is used to improve charged particles suppression. The solid angle defining counter is the active NaI-converter CV. The trigger counter of 18cm diameter rejects particles which are entering the NaI too close to the border.

The large NaI(Tl) one-crystal is encased by a protecting *Al* cylinder and the scintillation light is viewed by 7 photomultipliers.

SIN-NaI Electronics

The logical signals of the two charged particles anticounters AC and AC2 are OR-ed and inverted. Each of the analog signals of CV, $\bar{C}$ and T are measured by ADC's. The coincidence of all three logic signals indicates a conversion of a γ into a e^+e^- -pair:

$$\acute{e} = CV \wedge \bar{C} \wedge T$$

The signals of the 7 photomultipliers are added and amplified by a factor of 10 in the experimental area to improve signal to noise ratio. An analog signal is fed to an ADC. A logic signal is generated independently by two constant fraction discriminators (CFD), one NAI_{LOW} with a low threshold and a short output signal ($\sim 5ns$) to define the exact time, the other NAI_{HIGH} with a high threshold and a longer output signal ($\sim 20ns$) to define the low-energy threshold which can thus be varied without changing the timing. This method of double CFD's also reduces walk without triggering on noise. An event is given by

$$e^- = AC \wedge \acute{e} \wedge NAI$$

or by

$$\gamma_{conv} = \overline{AC} \wedge \acute{e} \wedge NAI$$

or by

$$\gamma_{non-conv} = \overline{AC} \wedge \bar{e} \wedge NAI$$

with $NAI \wedge NAI_{HIGH} \wedge NAI_{LOW}$.

Appendix B

Monitoring of Time Calibration

For the monitoring of the various time calibrations high energy pion-induced photons ($90 \text{ MeV} \leq E_\gamma \leq 145 \text{ MeV}$) are used. The time calibrations which have to be monitored are: Δt_{RF-NaI} because this is the principal time spectrum for the asymmetry measurement, Δt_{NaI-M1} , Δt_{NaI-H3} , Δt_{NaI-H4} and Δt_{NaI-H5} because they are essential for the prompt subtraction procedure. For all of these time spectra, the position of the prompt peak (the two prompt peaks in the case of Δt_{RF-NaI}) is determined by fitting a gaussian onto it. The results of these fits can be found in the following tables and are plotted in the respective figures. A time offset value was calculated for every run to bring the prompt peaks of one time spectrum to a certain position (arbitrary but fixed for one time spectrum and all runs).

Table B.1: Monitoring of time calibration for Δt_{RF-NaI} with high energy π -induced γ for target OUT.

Run Number	Run Name	Arrival Time [0.5ns/bin]			
		Peak 1 Position ± 0.5	Peak 2 Position ± 0.5	Average Position ± 0.4	Correction Value @ 77.4
1	MOB1	56.7	96.5	76.6	+1.0
2	MOB4	57.6	95.6	76.6	+1.0
3	MOB5	54.6	97.1	75.9	+1.0
4	MOB9	56.5	95.7	76.1	+1.0
5	MOC4	56.0	97.0	76.5	+1.0
6	MOC7	56.3	95.8	76.1	+1.0
7	MCD3	55.8	95.0	75.4	+2.0
8	MCE2	54.7	94.5	74.6	+3.0
9	MCE3	57.3	96.3	76.8	+1.0
10	MOF3	54.9	95.9	75.4	+2.0
11	MOF5	56.1	95.6	75.9	+2.0
12	MOH0	56.6	95.0	75.8	+2.0
13	MOI1	55.4	96.0	75.7	+2.0
14	MOJ8	56.0	95.8	75.9	+1.0
Average Position of all Runs				76.0 ± 0.6	

For the time spectra Δt_{RF-NaI} the positions of two prompt peaks are determined. The third peak which is visible lies partially outside of the gate for this time spectrum; a position determination is therefore not precise enough. Also listed in tables B.1 and B.2 is the average position of the two prompt peaks. This average position is also shown in figure B.1 with circles. The correction offset for each run is calculated from the difference of this average position and the dashed line. All values in the tables are given in bins with $0.5ns/bin$.

Table B.2: Monitoring of time calibration for Δt_{RF-NaI} with high energy π -induced γ for target IN.

Run Number	Run Name	Arrival Time [0.5ns/bin]			
		Peak 1 Position ± 0.5	Peak 2 Position ± 0.5	Average Position ± 0.4	Correction Value @ 77.4
1	MCA9	57.2	97.8	77.7	-
2	MCB2	56.7	97.3	77.0	-
3	MCB3	56.0	97.6	76.8	+1.0
4	MCB8	58.5	97.3	77.9	-1.0
5	MCC2	57.0	97.6	76.8	+1.0
6	MCC3	57.3	96.3	76.8	+1.0
7	MCC5	59.5	96.4	78.0	-1.0
8	MCC6	57.8	95.5	76.7	+1.0
9	MCD2	57.4	96.8	77.1	-
10	MCD4	58.2	96.4	77.3	-
11	MCD5	59.0	95.8	77.4	-
12	MCD6	57.6	96.8	77.2	-
13	MCD7	56.9	94.8	75.9	+2.0
14	MCD8	56.7	96.9	76.8	+1.0
15	MCD9	56.7	97.4	77.0	-
16	MCE0	55.7	97.2	76.5	+1.0
17	MCE1	56.8	97.2	77.0	-
18	MCE8	58.2	96.6	77.4	-
19	MCE9	57.5	97.1	77.3	-
20	MCF0	57.5	96.9	77.2	-
21	MCF1	57.2	97.2	77.2	-
22	MCF2	57.6	95.7	76.7	+1.0
23	MCF6	57.9	97.2	77.6	-
24	MCG0	59.0	97.4	78.2	-1.0
25	MCG3	57.1	96.8	77.0	-
26	MCG4	57.1	96.8	77.0	-
27	MCG5	57.7	97.6	77.7	-
28	MCH1	56.7	95.7	76.2	+1.0
29	MCH2	55.8	96.3	76.1	+1.0
30	MCH6	56.0	97.1	76.6	+1.0
31	MCH9	56.7	98.1	77.4	-
32	MCI0	57.0	97.5	77.3	-
Average Position of all Runs				77.1 ± 0.5	

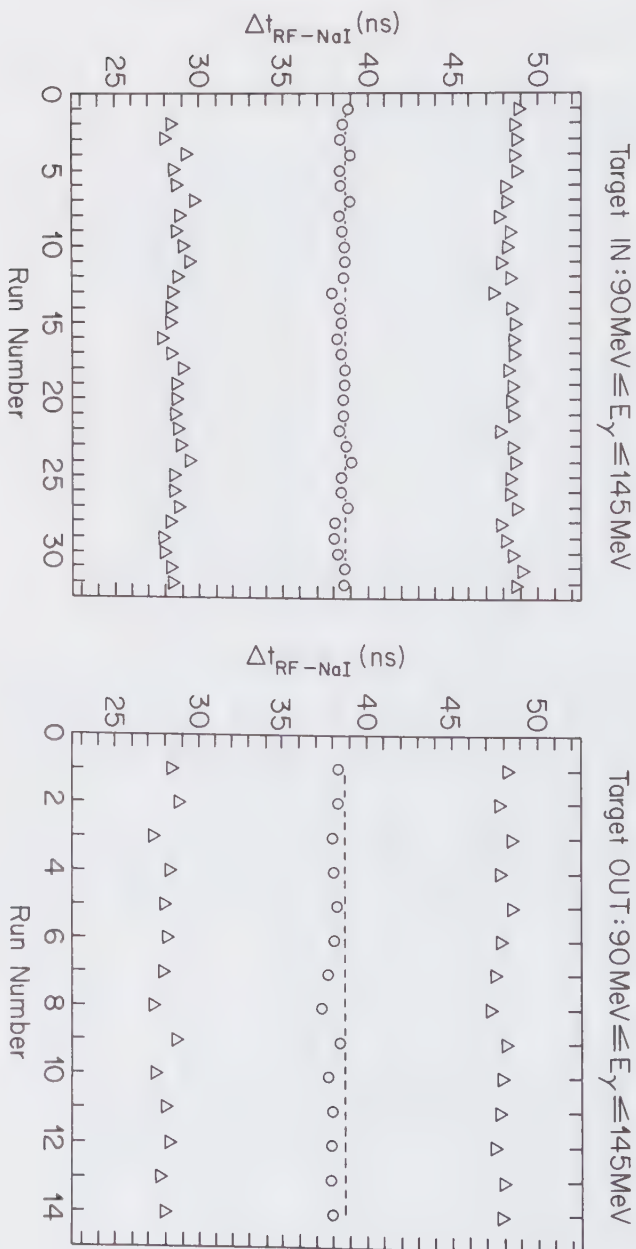


Figure B.1: Monitoring of time calibration for $\Delta t_{\text{RF-NaI}}$ for target IN and target OUT. (Triangles: positions of 1. and 2. prompt peak; circles: average position).

Table B.3: *Monitoring of time calibration for hodoscope time spectra with high energy π -induced γ for target OUT.*

Run Number	Run Name	Arrival Time [0.5ns/bin]			
		Δt_{NaI-M1} Pos. Width ± 0.1	Δt_{NaI-H3} Pos. FWHM ± 0.1	Δt_{NaI-H4} Pos. FWHM ± 0.1	Δt_{NaI-H5} Pos. FWHM ± 0.1
1	MOB1	131.9 ± 13.9	75.4 ± 9.3	74.3 ± 10.9	74.3 ± 10.9
2	MOB4	131.3 ± 15.0	74.3 ± 10.9	74.5 ± 13.4	74.5 ± 13.3
3	MOB5	131.7 ± 12.5	75.2 ± 9.6	74.4 ± 11.7	74.2 ± 10.3
4	MOB9	131.3 ± 14.0	74.8 ± 11.8	74.4 ± 12.5	74.4 ± 12.5
5	MOC4	131.6 ± 14.7	74.8 ± 11.3	74.9 ± 13.2	74.9 ± 13.2
6	MOC7	132.8 ± 12.8	75.0 ± 10.2	75.3 ± 13.0	75.3 ± 13.1
7	MOD3	132.1 ± 13.9	74.6 ± 10.4	74.2 ± 13.6	74.2 ± 13.6
8	MCE2	132.0 ± 13.8	74.0 ± 9.0	73.6 ± 15.2	73.2 ± 15.2
9	MCE3	132.3 ± 14.2	74.8 ± 9.6	74.0 ± 11.7	74.0 ± 11.7
10	MOF3	132.6 ± 12.8	74.8 ± 8.9	75.7 ± 13.4	75.7 ± 13.4
11	MOF5	133.1 ± 13.1	75.0 ± 9.7	75.1 ± 11.0	75.1 ± 11.0
12	MOH0	132.4 ± 13.4	74.7 ± 10.0	74.8 ± 13.6	74.8 ± 13.6
13	MOI1	132.5 ± 12.1	74.9 ± 11.3	74.2 ± 12.3	74.2 ± 12.3
14	MOJ8	132.7 ± 13.2	75.1 ± 12.3	74.8 ± 10.3	74.8 ± 10.3
uncorrected		$132.2 (\pm 0.6)$	$74.8 (\pm 0.4)$	$74.6 (\pm 0.6)$	$74.6 (\pm 0.6)$

Table B.4: Monitoring of time calibration for hodoscope time spectra with high energy π -induced γ for target IN.

Run Number	Run Name	Arrival Time [0.5ns/bin]			
		Δt_{NaI-M1} Pos. Width ± 0.1	Δt_{NaI-H3} Pos. FWHM ± 0.1	Δt_{NaI-H4} Pos. FWHM ± 0.1	Δt_{NaI-H5} Pos. FWHM ± 0.1
1	MCA9	131.5 ± 10.3	73.8 ± 8.0	73.5 ± 8.3	73.5 ± 8.3
2	MCB2	131.8 ± 11.2	74.9 ± 7.1	74.1 ± 11.7	74.1 ± 11.7
3	MCB3	131.8 ± 10.1	75.0 ± 7.1	74.7 ± 10.2	74.7 ± 10.4
4	MCB8	131.6 ± 11.8	74.3 ± 8.0	74.3 ± 8.0	74.3 ± 8.1
5	MCC2	132.4 ± 9.4	75.2 ± 8.4	74.8 ± 9.1	74.8 ± 9.1
6	MCC3	132.3 ± 11.3	75.0 ± 7.7	74.7 ± 10.5	74.7 ± 10.5
7	MCC5	131.9 ± 13.1	75.1 ± 7.3	74.7 ± 12.1	74.7 ± 12.1
8	MCC6	132.1 ± 11.4	75.1 ± 7.5	74.5 ± 9.4	74.5 ± 9.5
9	MCD2	131.9 ± 10.3	74.6 ± 7.1	74.2 ± 10.5	74.2 ± 10.5
10	MCD4	131.6 ± 11.9	73.9 ± 7.7	73.6 ± 12.0	73.7 ± 12.0
11	MCD5	132.3 ± 11.4	74.1 ± 7.1	73.6 ± 8.4	73.6 ± 8.4
12	MCD6	132.1 ± 12.0	74.3 ± 7.3	74.2 ± 9.3	74.2 ± 9.2
13	MCD7	132.1 ± 11.8	74.4 ± 8.8	74.6 ± 12.6	74.6 ± 12.6
14	MCD8	132.2 ± 11.8	74.6 ± 7.4	73.7 ± 9.6	73.7 ± 9.8
15	MCD9	131.7 ± 11.8	74.4 ± 8.0	73.9 ± 9.8	73.9 ± 9.7
16	MCE0	132.4 ± 12.0	74.7 ± 8.0	74.3 ± 11.1	74.2 ± 10.9
17	MCE1	132.0 ± 12.0	74.4 ± 8.0	74.0 ± 11.9	74.9 ± 11.0
18	MCE8	132.3 ± 11.0	74.5 ± 6.5	74.2 ± 10.0	74.2 ± 10.0
19	MCE9	132.0 ± 11.4	74.4 ± 7.7	73.7 ± 8.0	73.7 ± 8.1
20	MCF0	132.9 ± 11.4	74.3 ± 7.5	74.0 ± 9.1	74.0 ± 9.1
21	MCF1	132.2 ± 11.6	74.1 ± 7.0	73.6 ± 7.8	73.6 ± 7.8
22	MCF2	132.3 ± 11.6	74.8 ± 7.9	74.6 ± 11.9	74.6 ± 11.6
23	MCF6	132.3 ± 12.8	74.8 ± 7.8	74.1 ± 10.7	74.1 ± 10.7
24	MCG0	132.2 ± 11.0	74.1 ± 8.2	74.6 ± 11.3	74.6 ± 11.3
25	MCG3	131.9 ± 11.5	73.7 ± 8.1	73.5 ± 8.9	73.5 ± 8.9
26	MCG4	131.9 ± 12.4	74.1 ± 8.7	74.2 ± 9.9	74.2 ± 9.9
27	MCG5	132.4 ± 10.9	74.6 ± 7.6	74.2 ± 9.0	74.2 ± 9.0
28	MCH1	132.9 ± 12.2	74.9 ± 7.9	74.7 ± 11.9	74.7 ± 11.9
29	MCH2	132.5 ± 11.8	75.1 ± 7.5	74.5 ± 9.5	74.5 ± 9.5
30	MCH6	133.4 ± 12.1	75.9 ± 7.8	75.0 ± 11.8	75.0 ± 11.7
31	MCH9	132.8 ± 11.7	74.9 ± 7.2	75.2 ± 11.5	75.2 ± 11.5
32	MCIO	132.4 ± 10.8	74.9 ± 7.7	74.5 ± 10.0	74.5 ± 10.0
uncorrected		$132.2 (\pm 0.4)$	$74.6 (\pm 0.5)$	$74.3 (\pm 0.5)$	$74.3 (\pm 0.5)$

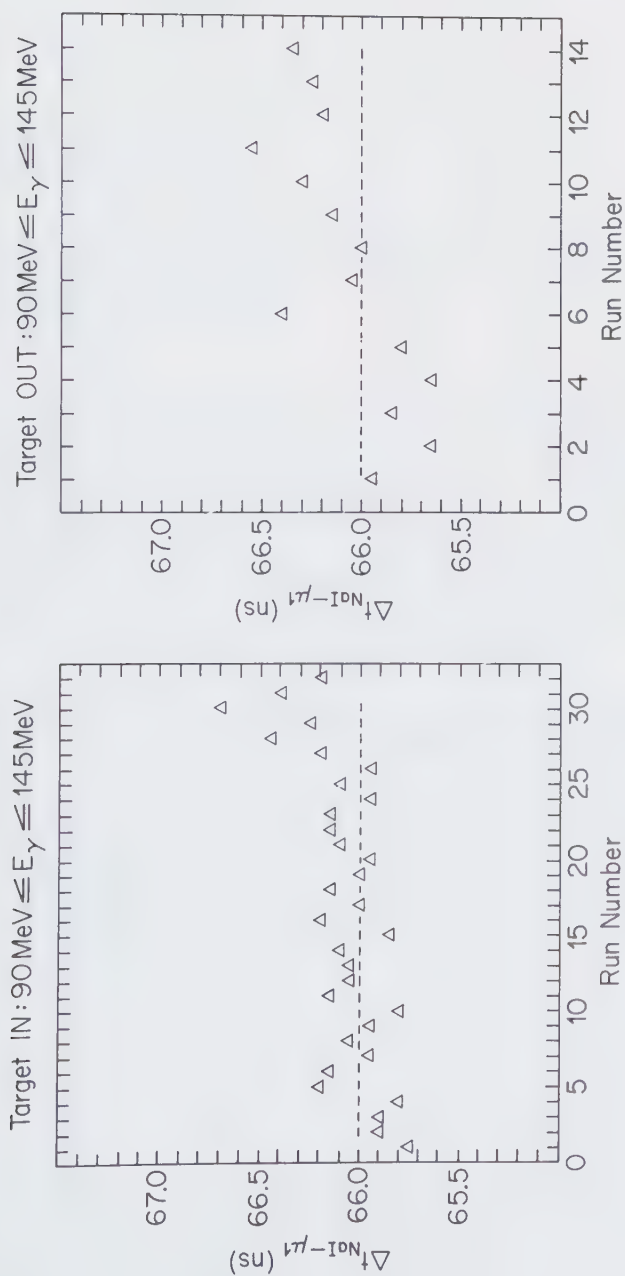


Figure B.2: Monitoring of time calibration for $\Delta t_{IN} - t_{IN}$ for target IN and target OUT.

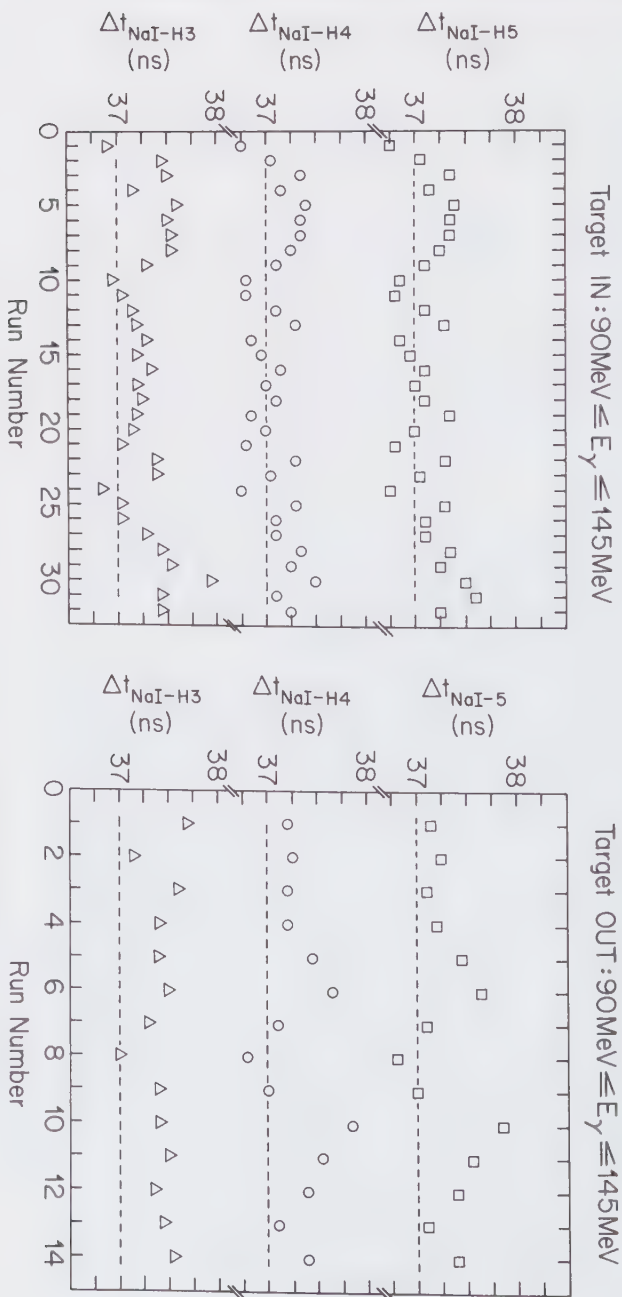


Figure B.3: Monitoring of time calibration for $\Delta t_{\text{NaI-H}_n}$ for target IN and target OUT.

Appendix C

Energy Dependence of Time Measurements

The determination of any eventual energy dependence in the time measurements is made with “converted photons” from RPC on CH_2 . To discriminate additionally against neutrons a time of flight window for photons is used. The position of the prompt peak of photons out of a certain energy band can be determined by fitting a gaussian onto it. The resulting values of these fits are given in the following tables and graphically displayed in the respective diagram. The positions of a peak are plotted at the average energy of the respective energy band.

For all time spectra walk is found but in the case of the asymmetry time spectrum in the opposite direction. This is the result of a small overcorrection due to the primary walk compensation described in section 4.2.7. To calculate the walk compensation for each time spectrum a straight line is fitted through the points in the interesting energy region between 60 MeV and 145 MeV. The parameters of the straight line are used to calculate the walk compensation for all dense data analysis.

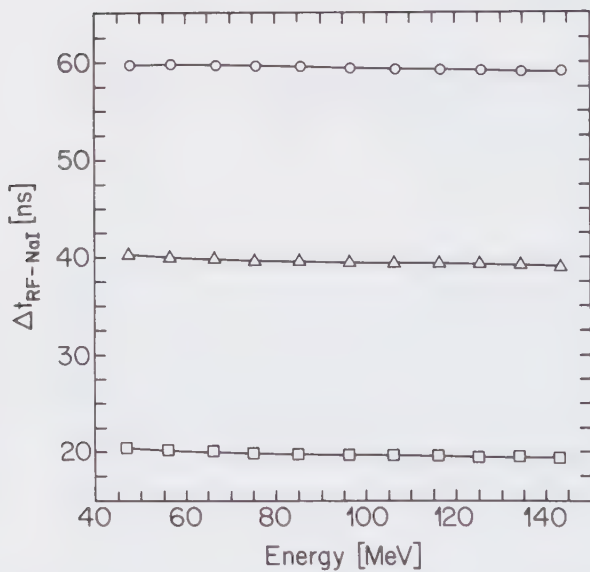


Figure C.1: Energy dependence of Δt_{RF-NaI} for photons. A small overcorrection is clearly visible.

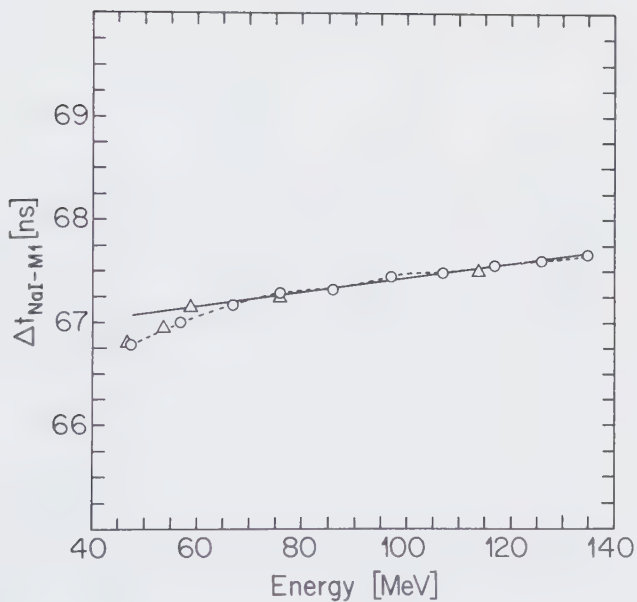


Figure C.2: Energy dependence of Δt_{NaI-M1} for photons. The triangles show the measured arrival times for their respective 10 MeV intervals. The straight line is a fit to the measured points from 60 MeV to 140 MeV.

Table C.1: Energy dependence of Δt_{RF-NaI} for photons.

Energy Range [MeV]	Average Energy [MeV]	Arrival Time [0.5ns/bin] $\pm \leq 0.5$		
		Peak FWHM	Peak FWHM	Peak FWHM
40–50	47	40.9 ± 7.5	80.7 ± 8.2	119.6 ± 7.7
50–60	56	40.50 ± 7.7	80.03 ± 7.7	119.73 ± 7.5
60–70	66	40.28 ± 7.3	79.84 ± 7.2	119.49 ± 7.3
70–80	75	39.82 ± 7.1	79.37 ± 7.1	119.31 ± 7.3
80–90	85	39.63 ± 7.2	79.33 ± 7.0	119.22 ± 6.9
90–100	96	39.40 ± 7.2	79.13 ± 7.3	118.93 ± 7.3
100–110	106	39.35 ± 7.0	78.90 ± 7.1	118.73 ± 7.2
110–120	116	39.25 ± 7.1	78.88 ± 7.0	118.57 ± 6.9
120–130	125	39.00 ± 7.0	78.82 ± 7.1	118.50 ± 6.9
130–140	134	39.10 ± 7.4	78.67 ± 6.9	118.28 ± 6.8
140–150	143	38.9 ± 9.2	78.2 ± 8.6	118.3 ± 7.8

Table C.2: *Energy dependence of Δt_{NaI-M1} for photons.*

Energy Range [MeV]	Average Energy [MeV]	Arrival Time [0.5ns/bin]	Peak width FWHM [0.5ns/bin]
40–50	47	133.56 ± 0.07	± 7.1
50–60	56	134.00 ± 0.04	± 7.0
60–70	66	134.34 ± 0.05	± 7.0
70–80	75	134.57 ± 0.03	± 7.0
80–90	85	134.64 ± 0.03	± 6.9
90–100	96	134.91 ± 0.03	± 7.1
100–110	106	134.97 ± 0.03	± 6.9
110–120	116	135.12 ± 0.03	± 6.9
120–130	125	135.20 ± 0.03	± 6.8
130–140	134	135.31 ± 0.05	± 6.5
20–50	46	133.6 ± 0.7	± 7.3
50–55	53	133.9 ± 0.3	± 6.9
55–60	58	134.3 ± 0.8	± 7.0
60–90	75	134.5 ± 0.3	± 7.0
90–145	113	135.0 ± 0.3	± 7.0
145–200	151	135.5 ± 0.2	± 5.2

Table C.3: Energy dependence of Δt_{NaI-Hn} for photons.

Energy Range [MeV]	Average Energy [MeV]	TOF cuts for γ selection [0.5ns/bin]	Arrival Time [0.5ns/bin]	Peak Width FWHM [0.5ns/bin]
Histogram EVH2				
20-50	46	70-80	75.00 ± 0.13	5.9
50-55	53	71-81	75.61 ± 0.10	5.5
55-60	58	71-81	76.03 ± 0.08	4.9
60-90	75	72-82	76.85 ± 0.03	5.1
90-145	113	73-83	77.80 ± 0.03	5.1
Histogram EVH3				
20-50	46	71-81	75.03 ± 0.13	5.9
50-55	53	72-82	76.53 ± 0.07	5.3
55-60	58	72-82	76.81 ± 0.06	5.4
60-90	75	73-83	77.50 ± 0.02	5.1
90-145	113	74-84	78.40 ± 0.02	5.1
Histogram EVH4				
20-50	46	74-84	78.43 ± 0.09	6.0
50-55	53	74-84	78.82 ± 0.07	5.2
55-60	58	74-84	79.39 ± 0.06	5.2
60-90	75	75-85	80.00 ± 0.02	5.2
90-145	113	76-86	80.95 ± 0.02	5.1
Histogram EVH5				
20-50	46	74-84	78.42 ± 0.09	6.1
50-55	53	74-84	78.83 ± 0.06	5.2
55-60	58	74-84	79.39 ± 0.06	5.2
60-90	75	75-85	80.00 ± 0.02	5.2
90-145	113	76-86	80.96 ± 0.02	5.1
Histogram EVH6				
20-50	46	72-82	76.2 ± 0.2	6.2
50-55	53	72-82	76.0 ± 0.2	4.9
55-60	58	72-82	76.8 ± 0.1	5.3
60-90	75	73-83	77.00 ± 0.05	5.1
90-145	113	74-84	77.85 ± 0.06	5.8

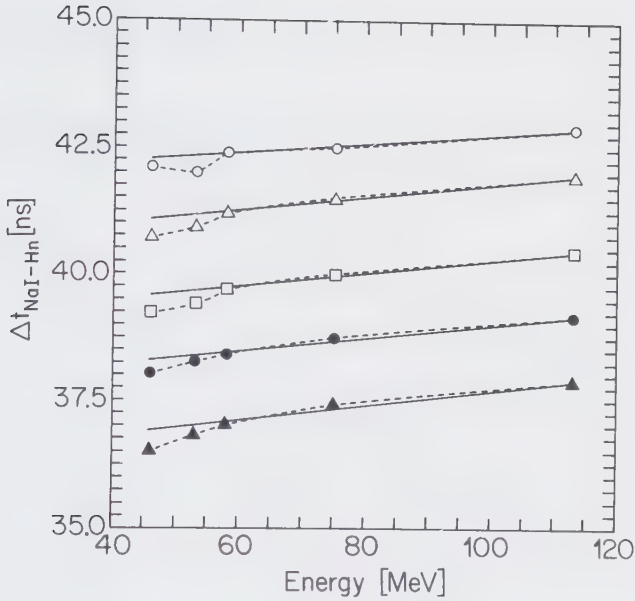


Figure C.3: Energy dependence of $\Delta t_{\text{NaI-Hn}}$ for photons. The symbols show the measured arrival times for their respective energy intervals. The straight lines are fits to the measured points from 60 MeV to 140 MeV. Some artificial offset has been introduced in the diagram to make the points for the different hodoscopes distinguishable. Hodoscope H1 contains too little events to allow a determination of the prompt position in various energy bands.

Appendix D

Neutron Background

Table D.1: Comparison of the relative number of bars per event for events with $60\text{MeV} \leq E \leq 90\text{MeV}$.

	Relative Number of Bars per Event						
	1	2	3	4	5	6	7
Pure γ	3.7%	20.6%	33.2%	25.9%	12.2%	3.5%	0.8%
Pure n	39.8%	32.7%	16.6%	7.9%	2.4%	0.5%	0.2%
γ target-IN	10.5%	28.3%	32.4%	19.1%	7.0%	1.9%	0.5%
γ target-OUT	12.4%	28.8%	31.7%	18.0%	6.5%	1.8%	0.5%
γ IN – OUT	7.6%	27.5%	33.4%	20.8%	7.8%	2.1%	0.5%

Table D.2: Energy dependence of the average number of bars for γ events and n events respectively.

Energy Range [MeV]	Average Energy [MeV]	Number of Bars	
		γ	n
		Average σ FWHM	Average σ FWHM
40–50	47	$2.86 \pm 0.02 \pm 2.5$	$0.97 \pm 0.07 \pm 3.7$
50–60	56	$3.40 \pm 0.01 \pm 2.7$	$0.89 \pm 0.08 \pm 4.1$
60–70	66	$3.59 \pm 0.01 \pm 2.8$	$0.64 \pm 0.11 \pm 4.5$
70–80	75	$3.81 \pm 0.01 \pm 2.8$	$0.90 \pm 0.11 \pm 4.4$
80–90	85	$4.07 \pm 0.01 \pm 2.9$	$0.79 \pm 0.14 \pm 4.5$
90–100	96	$4.39 \pm 0.01 \pm 2.9$	$0.71 \pm 0.20 \pm 4.6$
100–110	106	$4.58 \pm 0.01 \pm 2.9$	$0.76 \pm 0.27 \pm 5.4$
110–120	116	$4.74 \pm 0.01 \pm 2.9$	$2.45 \pm 0.12 \pm 4.7$
120–130	125	$4.85 \pm 0.01 \pm 2.9$	$3.37 \pm 0.08 \pm 4.3$
130–140	134	$4.91 \pm 0.01 \pm 2.8$	$3.84 \pm 0.13 \pm 4.5$

Table D.3: Neutron Subtraction Factors as used to create neutron-free time spectra by subtracting the respective fraction of neutron-only time spectra.

Neutron Subtraction Factor SF				
Energy Range [MeV]	Target-IN		Target-OUT	
	> 1 Bar	> 2 Bar	> 1 Bar	> 2 Bar
60 – 65	0.725	0.201	0.759	0.205
65 – 70	0.802	0.243	0.974	0.289
70 – 80	1.058	0.345	1.273	0.405
80 – 90	1.207	0.429	1.358	0.473

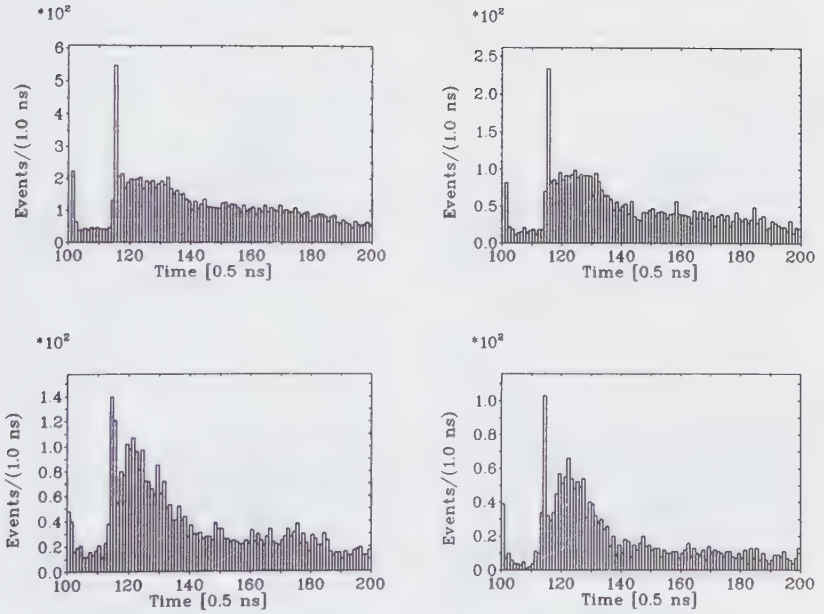


Figure D.1: Time spectra $\Delta t_{NaI-\mu 1}$ for 1-bar events and target IN in 4 energy bands: 60 MeV–65 MeV, 65 MeV–70 MeV, 70 MeV–80 MeV, 80 MeV–90 MeV.

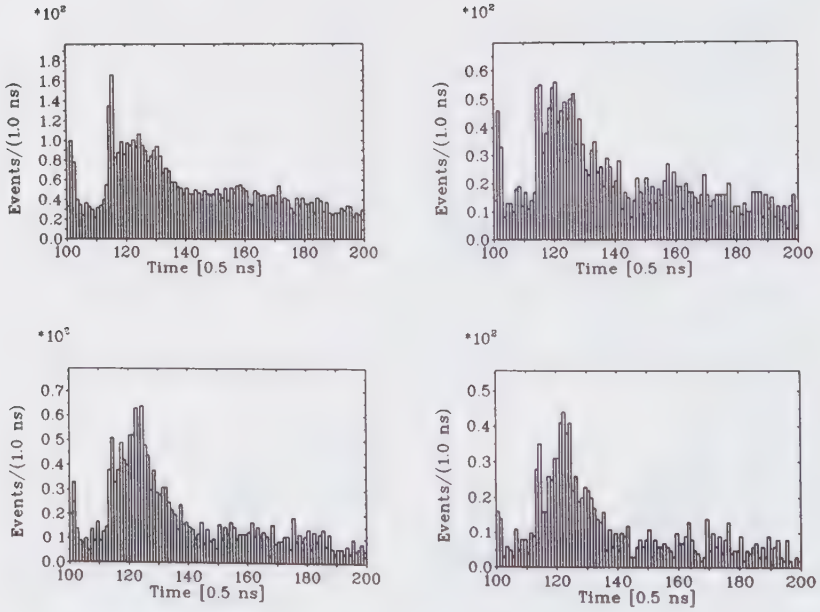


Figure D.2: Time spectra $\Delta t_{NaI-\mu 1}$ for 1-bar events and target OUT in 4 energy bands: 60 MeV–65 MeV, 65 MeV–70 MeV, 70 MeV–80 MeV, 80 MeV–90 MeV.

Appendix E

Prompt Subtraction

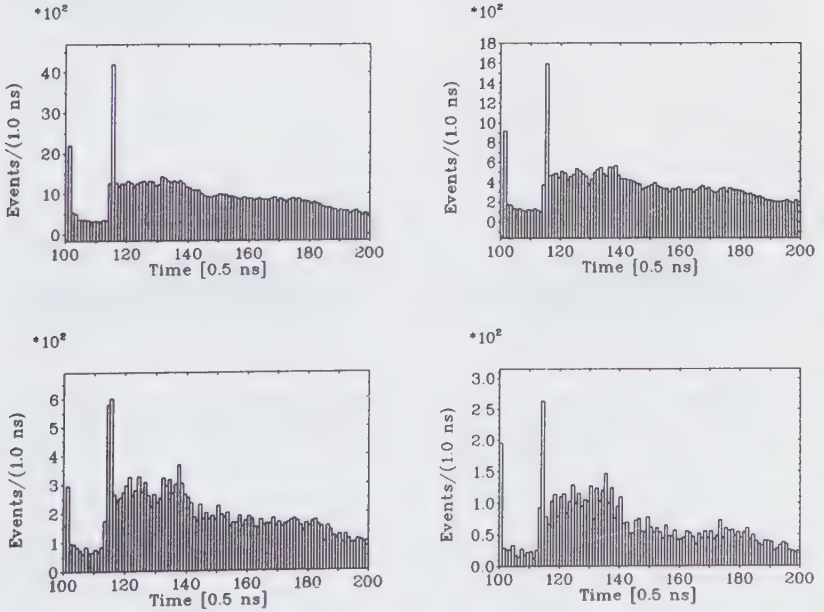


Figure E.1: Time spectra $\Delta t_{NaI-\mu 1}$ for target 1N and the four energy ranges 60–65 MeV, 65–70 MeV, 70–80 MeV, 80–90 MeV (top left to bottom right).

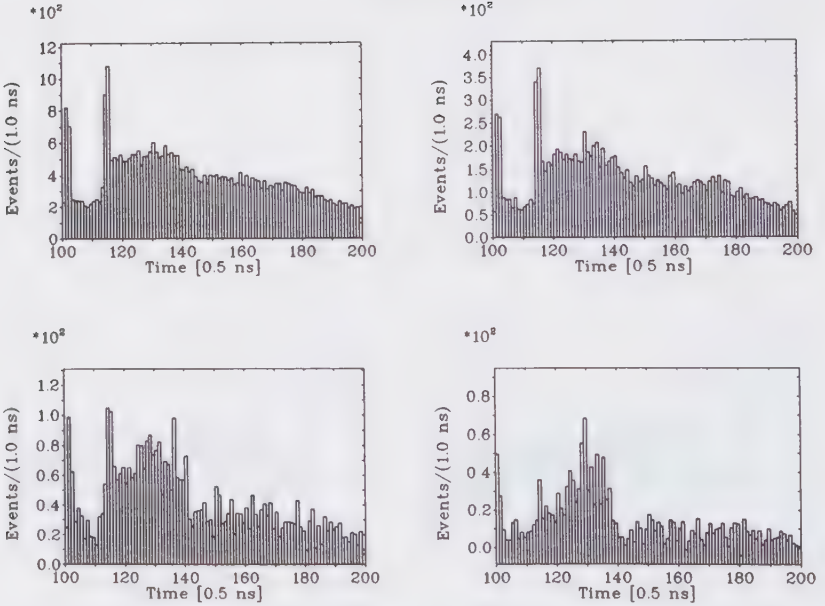


Figure E.2: Time spectra $\Delta t_{NaI-\mu 1}$ for target OUT and four energy ranges 60-65 MeV, 65-70 MeV, 70-80 MeV, 80-90 MeV (top left to bottom right).

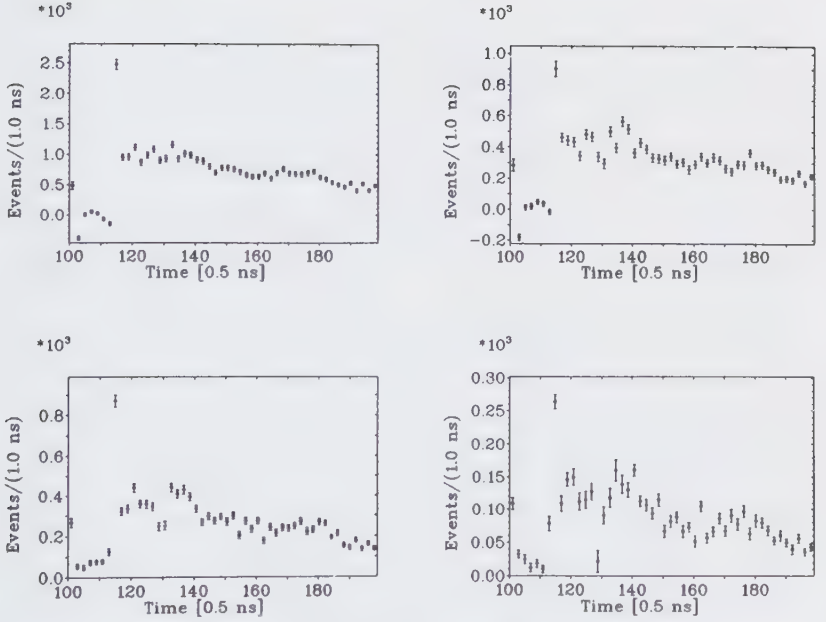


Figure E.3: Time spectra $\Delta t_{N\alpha I-1\alpha 1}$ for target IN-OUT and the four energy ranges 60-65 MeV, 65-70 MeV, 70-80 MeV, 80-90 MeV (top left to bottom right).

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